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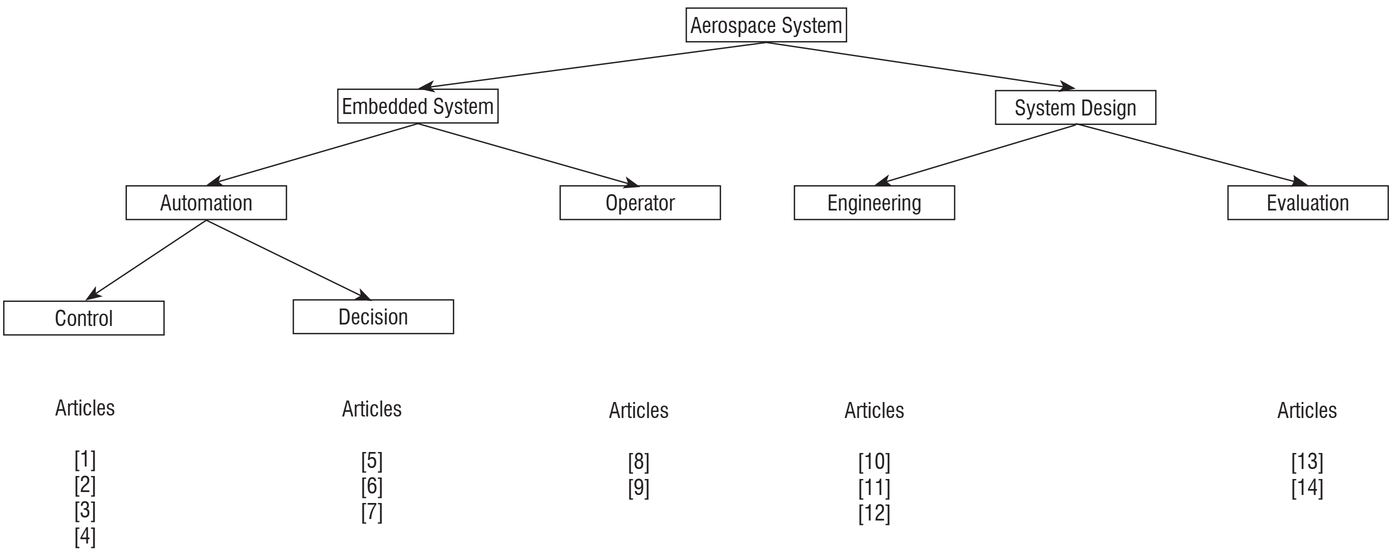
Mastering Complexity: an Overview

Aerospace systems are certainly part of those of which the complexity has been dramatically and continuously increasing for several decades. Not only are the vehicles increasingly more sophisticated but, since they are interacting increasingly with other so-called "intelligent" systems, human or machines, the overall system is even more complex.

Here, the word "complexity" is used in the common sense: it just means "too big to fit in the head of a human being". We undertake projects that are always aimed beyond the previous ones and we now face challenges that cannot be addressed without the aid of information technologies, which extend human capabilities. We are at a point where the matter is not "simply" to invent new systems, but to invent codes that will help to invent new complex systems.

This fourth Aerospace Lab issue is dedicated to various techniques used to address some of the most difficult issues in complex aerospace system design. It is not focused on a sub-class of aspects; it is a gallery of articles that will encompass the main issues to be addressed when considering advanced aerospace systems. There are two groups of articles: those related to embedded system concepts and those related to concept design aid.



Embedded system information processing components

Flexible aircraft control

Modern aircraft (A/C) flight qualities result from the permanent interaction between aeroelastic phenomena and close-to-actuator control laws, even in manually piloted mode. New materials allow A/C to be lighter and larger; in return they offer multiple structure flexible modes which slowly slip as fuel weight decreases and as the flight point changes. It is essential for the control laws to be robust to these variations, i.e., that they provide good flight qualities in all configurations. The Theory of Control offers methods for computing robust laws but a naïve approach fails with realistic flexible aircraft, since their model dimension may be as large as several hundred. Recent advances in control law synthesis for high-dimensioned systems are presented in [1]. Robust control laws are optimized given an A/C nominal model and an associated model of uncertainty. Of course, the smaller the uncertainty, the more performing the control is. Therefore, the quality of the nominal model is essential and this is the flight test purpose, to collect data to identify a precise A/C dynamic model, including structure flexible modes. This task is complicated by the model dimension and by the need to process flight test data very quickly, since the flight test campaigns are expensive. [2] gives an overview of the most efficient techniques. However, the model resulting from flight test data processing is generally of unnecessarily large dimension for robust law synthesis purposes and model reduction must be considered. The Linear Fractional Representation (LFR) presented in [3] is especially well suited for reducing the model order.

Close-to-environment flight control

For most existing automatic aerial platforms, the navigation task relies only on proprioceptive sensors (inertial, pressure, pitot sensors) possibly coupled with GPS limiting their cases of use to obstacle-free areas. Flying low among obstacles, possibly without GPS, can be addressed using optical sensors delivering measurements relative to the surrounding environment. As shown in [4], managing the platform from this kind of sensors can take on several forms, from designing piloting or guidance laws compatible with non-metric low level visual measurements, to inferring 3D information or GPS-like measurements by computer vision and scene understanding.

Closed-loop on-line decision making

Before the numeric age, only analogue electronics or electromechanical devices could implement control law correctors fed with continuous signals and Boolean information. Then, computers allowed more general symbolic data to be dealt with also: on-board automated reasoning became possible, "artificial intelligence"(1) would follow and robots could be imagined. Note, however, that torpedoes were already simple, but genuine, operational robots. Drones and missiles are the target applications in the aerospace field, but it is clear that classic civil A/C and helicopters will benefit from intelligence capabilities, by even more efficient new pilot assistance. Automated decision is a key issue for space systems.

Motion control is obtained by the cooperation between three basic functions: sensing, state estimation and control signal computation. Likewise, robot "intelligence" is based on the cooperation between perception, situation assessment and decision. Research in artificial intelligence has been underway for more than 30 years and we are still far from being able to make robots as smart as C-3PO or R2D2. However, knowledge has been acquired and efficient methods exist for decision making in realistic contexts, in particular on-line decision-making under uncertainty and partial observability, as presented in [5]. For a drone scenario, a scene understanding layer must provide the decision layer with situation assessment information. Which objects are in the scene? Where? What is the relative location of the drone with respect to the local scene? As explained in [6] scene understanding is a very difficult task. As it is unrealistic to describe a priori all of the objects that may be encountered, learning techniques must be considered. How what is expected to be encountered should be encoded, depending on the sensors used, is also a very hard problem.

Fusing heterogeneous information

The "system of systems" military concept refers to a set of autonomous systems that must coordinate in order to perform a given action, none of these being able to perform it alone. Situation assessment is one of such actions and requires information provided by several types of sources to be merged, some of them being human. In the future, UAVs will be part of systems of systems. They must thus participate in situation assessment based on the signal that they collect with their own sensor, or with the sensors of the other UAVs, as well as on high level information provided by humans. [7] addresses the question of fusing human reports for intelligence purposes. It shows a methodology that has proven to be compliant with NATO recommendations.

Evolution of the pilot role

Few systems are really "autonomous". Except for "fire and forget" weapons, there is(are) always a (or several) human operator(s) somewhere in the loop. Drones and satellites are monitored from control stations. Increasingly more pilot assistance will be introduced in the cockpits of aircraft and helicopters: the role of the pilot is changing and it can be foreseen that at some future time transport aircraft will basically not differ from drones, except that they will have an operator on-board (maybe). Then, two difficult problems arise.

First, since the automated systems are certified to perform safe management and since the operator is licensed to be competent, how should a conflict between human and machine be managed? This problem analysis and modeling is presented in [8].

Second, since the automated system makes decisions without referring every time to the operator, for the sake of reducing the workload for instance, the operator may lose the sensation that he/she is still in control of the system. He/she could feel disconnected, loose his/her situational awareness and the result may be catastrophic. "Sense of agency" (= feeling of being an agent) is a new formalism, presented in [9], suited for modeling and analyzing this problem.

(1) Of course, this sort of "intelligence" should not be compared to human, or animal, intelligence.

Designing aerospace systems

So far, we have considered issues about aerospace system real-time information processing. We now address issues about how aerospace systems, software and avionics should be designed on the one hand, and about how vehicle architecture should be designed on the other hand.

Formal methods for software verification

The software volume on an A300 (first flight: 1972) was about 2 million lines of code. For an A380 (first flight: 2005) it exceeds 100 million lines of code. It is clear that correctness cannot be checked without computer assistance. This is not specific to aerospace; other sorts of critical systems (automobiles, trains and nuclear power plants) encounter the same concerns. The research effort, summarized in [10], is aimed at developing generic tools based on formal methods, to describe the system at several level of abstraction, including the safety requirements, and to perform automated verification.

Avionics challenges

Avionic system implementation also dramatically changed from the 80's, when sub-systems had their own dedicated computer and interacted through dedicated links. Modern design is based on Integrated Modular Avionics (IMA), which allows computing resource sharing with no-interference insurance. As shown in [11], IMA provides flexibility, which should lead to reconfiguration capabilities. [11] also addresses the problem of using a new multi-core generation of processors in future avionics.

Multidisciplinary Design Optimization

Vehicle architecture design benefits from the progress of multidisciplinary design optimization techniques (MDO). It allows fast dimensioning of entirely new concepts or, simply, evaluation of the potentialities of a new subsystem concept by tuning the other subsystems accordingly. Although several generic frameworks exist, achieving a realistic MDO environment requires the merging of several competences and practical experience, as explained in [12].

Large distributed simulation techniques

Formal property assessment is not always possible. In those cases, the use of simulation is necessary. However, Monte-Carlo techniques are not realistic when a combinatorial explosion of cases is to be explored and/or the system is time-dependent. Article [13] presents various techniques for coping with these problems, in particular when the architecture of the system can be formally described. When the system is too large, or when it includes heterogeneous sub-systems, typically when dealing with systems of systems, simulation remains the only means to assess the emerging behavior resulting from the interaction of several entities. Such simulation should be evolutionary, i.e., easy to modify when components are modified or, even, when components are added. Distributed simulation is a key technique, [14] presents operational methods based on the HLA standard.

14 articles are certainly much too few to properly deal with the entire problem addressed above, but a number of references will allow the reader to go further. However, important problems have not been addressed. For instance: automated system certification, fault detection, isolation and recovery and system of systems formal modeling. This is a good reason to think of a future Aerospace Lab issue ■

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Flight Control Laws: Recent Advances in the Evaluation of their Robustness Properties

This paper reviews a set of robustness analysis tools developed by the authors during the last decade to evaluate the robustness properties of high-dimensional closed-loop plants subject to numerous time-invariant uncertainties. These tools are used to compute both upper and lower bounds on the robust stability margin, the worst-case H_∞ performance level, as well as the traditional gain, phase, modulus and time-delay margins. The key idea is to solve the problem on just a coarse frequency grid and to perform a fast validation on the whole frequency range, which results in guaranteed but conservative bounds on the aforementioned quantities. Some heuristics are then applied to determine a set of worst-case parametric configurations leading to over-optimistic bounds. A branch and bound scheme is finally implemented, so as to tighten these bounds with the desired accuracy, while still guaranteeing a reasonable computational complexity. The proposed algorithms are successfully assessed on a challenging real-world application: a flight control law validation problem.

Introduction

Despite recent progress in computer-aided control design techniques, the development of flight control laws remains a challenging task. Even the most sophisticated approaches are still based on simplified models and fail to take all of the requirements into account during the first design phase. As a result, the validation process remains a major and possibly time-consuming issue. There is consequently an obvious need for robustness analysis tools which can be used to perform a reliable and fast preliminary evaluation of the designed controllers before the certification phase.

Among robustness analysis techniques (Lyapunov-based, SOS-based [2], IQC-based [14], …), μ-analysis is now considered as a classical and close to mature approach, which has proved to be useful in many applications (see e.g. [5] and included references). Nevertheless, some technical difficulties remain in specific fields such as robust stability and performance analysis of high-order plants involving largely repeated uncertainties. Indeed, despite recent achievements [19], [20], enhancements are still required to further reduce the conservatism while limiting the required computational time. In this context, the objective of this paper is to describe a set of algorithms and tools thanks to which robustness analysis becomes more reliable and less time-consuming. The ultimate goal is to reduce the number of iterations in a control design process and to avoid expensive Monte Carlo simulation campaigns.

The paper is organized as follows. The problem is first stated in the next section, where all of the key ingredients for μ-analysis are recalled. The robustness margins computation section is then devoted to the characterization of (skew-)μ upper bounds (with a particular emphasis on computational aspects), thanks to which guaranteed robustness margins are obtained. Next, in the worst case analysis section, computational approaches are proposed to determine some enhanced (skew-)μ lower bounds, which are used not only to quantify the conservatism, but also to identify some worst-case configurations useful for design purposes. Extensions of the above results are described in tools extensions section to compute worst-case gain, phase, modulus and delay margins. A branch and bound scheme is also proposed in this section in order to reduce the conservatism. The algorithms are finally illustrated on a challenging aircraft control application in the application to flight control laws validation section. Please note that this is a review paper, which presents the contributions of the systems control group of Onera to the field of μ-analysis. Some sections are thus covered quite briefly, but numerous references are provided throughout the paper.

Problem statement and motivations

Let us consider the standard interconnections of figure 1. $M(s)$ is a stable real-valued linear time-invariant (LTI) plant representing the nominal closed-loop system. Δ is a block-diagonal time-invariant operator, which contains all model uncertainties. For the sake of simplicity (see nevertheless remark 1), only parametric uncertainties are considered in this paper, which means that Δ is a matrix of the form:

$$\Delta = \mathrm{diag}\left(\delta_1 I_{n_1},\ldots,\delta_N I_{n_N}\right) \quad (1)$$

where the real scalars δ_i are said to be repeated if $n_i > 1$. Let $n=\sum_{k=1}^{N} n_k$. The set of real $n \times n$ matrices with the same structure as Δ in (1) is denoted by $\boldsymbol{\Delta}$, and $\boldsymbol{B}_\Delta = \left\{\Delta \in \boldsymbol{\Delta} : \bar{\sigma}(\Delta) < 1\right\}$, where $\bar{\sigma}(\bullet)$ denotes the largest singular value.

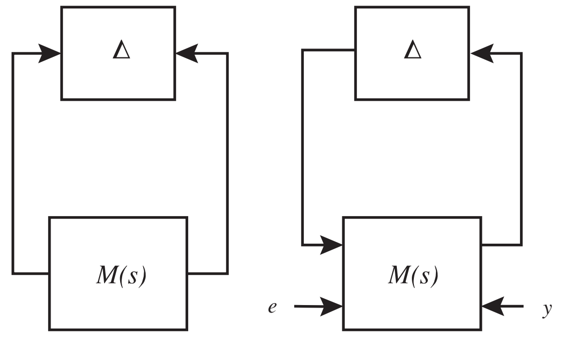

Figure 1 - Standard interconnections for robust stability (left) and robust performance (right) analysis

Two main issues are addressed in this paper: robust stability and worst-case H_∞ performance.

Problem 1 (robust stability) *Compute the maximum value $k_{\max}$ such that the interconnection of figure 1 (left) is stable $\forall \Delta \in k_{\max}\boldsymbol{B}_\Delta$, as well as a destabilizing perturbation $\tilde{\Delta} \in \boldsymbol{\Delta}$ such that $\bar{\sigma}(\tilde{\Delta}) = k_{\max}$.*

Problem 2 (worst-case H_∞ performance) *Assuming that the interconnection of figure 1 (right) is stable $\forall \Delta \in \boldsymbol{B}_\Delta$, compute the highest value $\gamma_{\max}$ of the H_∞ norm of the transfer matrix $F_u\left(M(s),\Delta\right)$ from e to y when Δ takes all possible values in $\boldsymbol{B}_\Delta$, as well as the corresponding value $\tilde{\Delta}$ of Δ.*

The most efficient technique to answer these two problems is certainly μ-analysis [3]. This is especially true when high-dimensional systems are considered. The underlying theory [17], [5] is not detailed in this paper but a few useful definitions are recalled below.

Definition 1 *Let ω_i be a given frequency. If no matrix $\Delta \in \boldsymbol{\Delta}$ makes $I - M(j\omega_i)\Delta$ singular, then the structured singular value $(s.s.v.)$ $\mu_\Delta\left(M(j\omega_i)\right)$ is defined as $\mu_\Delta\left(M(j\omega_i)\right) = 0$. Otherwise:*

$$\mu_\Delta\left(M(j\omega_i)\right) = \left[\min\left\{k \in \Re_+ : \exists \Delta \in k\boldsymbol{B}_\Delta, \det\left(I - M(j\omega_i)\Delta\right) = 0\right\}\right]^{-1} \quad (2)$$

The robustness margin $k_{\max}$ is then obtained as the inverse of the maximal value $\mu_\Delta\left(M(j\omega_i)\right)$ over the frequency range of interest Ω (usually equal to $\Re_+$):

$$k_{\max} = \left[\max_{\omega_i \in \Omega}\left\{\mu_\Delta\left(M(j\omega_i)\right)\right\}\right]^{-1} \quad (3)$$

The exact computation of $\mu_\Delta\left(M(j\omega_i)\right)$ is known to be NP hard in the general case, but both upper [25] and lower [24], [21] bounds can be determined using polynomial-time algorithms. An upper bound $\bar{\mu}_\Delta\left(M(j\omega_i)\right)$ provides a guaranteed but conservative value of the robustness margin when Ω is restricted to the single frequency ω_i, while a lower bound $\underline{\mu}_\Delta\left(M(j\omega_i)\right)$, usually associated with a worst-case parametric configuration $\tilde{\Delta}$, leads to an over-optimistic value.

Computing these bounds over the whole frequency range Ω is a challenging problem with an infinite number of both frequency-domain constraints and optimization variables. It is usually solved on a finite frequency grid $(\omega_i)_{i\in[1,M]}$ and an estimate of the robustness margin is then obtained as:

$$\frac{1}{\max\limits_{i\in[1,M]}\left\{\bar{\mu}_\Delta\left(M(j\omega_i)\right)\right\}} \le k_{\max} \le \frac{1}{\max\limits_{i\in[1,M]}\left\{\underline{\mu}_\Delta\left(M(j\omega_i)\right)\right\}} \quad (4)$$

However, a crucial problem appears in this procedure: the grid must contain the most critical frequency point for which the maximal value of $\mu_\Delta\left(M(j\omega_i)\right)$ is reached. If not, the upper bound on $k_{\max}$ can be very poor, notably in the case of flexible systems, whose μ plot often exhibits very high and narrow peaks. Even worse, the lower bound can be over-evaluated, $i.e.$ be larger than the real value of $k_{\max}$. Unfortunately, the aforementioned critical frequency is usually unknown. The same difficulty arises when worst-case H_∞ performance is considered. Problem 2 is indeed equivalent to a specific skew-μ problem [4]. Similarly to problem 1, it is thus commonly solved on a frequency grid using polynomial-time algorithms, leading to both lower [16] and (possibly under-estimated) upper [8], [9] bounds on $\gamma_{\max}$.

To overcome the above difficulty, [22] suggests to consider frequency as an additional parametric uncertainty, but this strategy usually leads to a computational burden when applied to high-dimensional systems. In this context, some alternative methods are proposed in this paper to compute both tight and reliable bounds on either $k_{\max}$ or $\gamma_{\max}$:

- Either a μ or a skew-μ upper bound is first computed at some frequency, for which nothing has been assessed yet. This bound is slightly increased, and a frequency interval on which it remains valid is computed. Such a strategy is repeated until the whole frequency range has been investigated, leading to either a lower bound on $k_{\max}$ or an upper bound on $\gamma_{\max}$. The latter is guaranteed over the whole frequency range, and not only on a frequency grid as is the case of most existing methods (see the Robustness margins computation section);
- Some heuristics are then proposed in the Worst case analysis section to determine a worst-case parametric configuration $\tilde{\Delta}$, such that the interconnection between $M(s)$ and $\tilde{\Delta}$ has an eigenvalue on the imaginary axis. Either an upper bound on $k_{\max}$ or a lower bound on $\gamma_{\max}$ is thus obtained. Unlike in most existing methods, frequency is an optimization parameter, which is used to detect critical frequencies and usually leads to more accurate bounds;
- A branch and bound algorithm is finally described in the Accuracy improvements section. It can be used to compute bounds with the desired accuracy and at a reasonable computational cost.

Note also that extensions of the aforementioned methods are proposed in the Unstructured margins section to solve the worst-case unstructured margins problem recalled below.

Problem 3 *(worst-case unstructured margins) With reference to figure 1 (left) and assuming that $k_{\max} > 1$, compute the smallest values of the gain, phase, modulus and time-delay margins when Δ takes all possible values in $\boldsymbol{B}_\Delta$.*

Robustness margins computation

Computation of a guaranteed stability margin

The classical way [25] to compute an upper bound on $\mu_\Delta(M(j\omega))$ for a given frequency point $\omega=\omega_i$ is to introduce two scaling matrices $D(\omega_i)$ and $G(\omega_i)$, which belong to specific sets **D** and **G** reflecting the block-diagonal structure and the real/complex nature of Δ.

Proposition 1 *Let β_i be a positive scalar. If there are some scaling matrices $D(\omega_i)\in\mathbf{D}$ and $G(\omega_i)\in\mathbf{G}$ such that:*

$$\bar{\sigma}\left(F(\omega_i)^{-\frac{1}{4}}\left\{\frac{D(\omega_i)M(j\omega_i)D(\omega_i)^{-1}}{\beta_i}-jG(\omega_i)\right\}F(\omega_i)^{-\frac{1}{4}}\right)\leq 1 \quad (5)$$

where $F(\omega_i)=I+G(\omega_i)^2$ and:

- $\mathbf{D}=\left\{D\in C^{n\times n}, D=D^*>0:\forall\Delta\in\mathbf{\Delta}, D\Delta=\Delta D\right\}$
- $\mathbf{G}=\left\{G\in C^{n\times n}, G=G^*:\forall\Delta\in\mathbf{\Delta}, G\Delta=\Delta^* G\right\}$

then $\mu_\Delta(M(j\omega))\leq\beta_i$.

Let us then slightly increase this upper bound, *i.e.* set $\beta_i\leftarrow(1+\varepsilon)\beta_i$, to enforce a strict inequality in condition (5). The key idea is now to compute the largest frequency interval $I(\omega_i)\ni\omega_i$ for which the increased upper bound and the scaling matrices remain valid, *i.e.* such that $\forall\omega\in I(\omega_i)$:

$$\bar{\sigma}\left(F(\omega_i)^{-\frac{1}{4}}\left\{\frac{D(\omega_i)M(j\omega)D(\omega_i)^{-1}}{\beta_i}-jG(\omega_i)\right\}F(\omega_i)^{-\frac{1}{4}}\right)\leq 1 \quad (6)$$

As is shown in proposition 2, the determination of $I(\omega_i)$ boils down to a standard eigenvalues computation [20].

Proposition 2 *Let (A_M,B_M,C_M,D_M) be a state-space representation of $M(s)$. Build the Hamiltonian-like matrix:*

$$\boldsymbol{H}=\begin{bmatrix}A_H & 0\\ -C_H^*C_H & -A_H^*\end{bmatrix}+\begin{bmatrix}B_H\\ -C_H^*D_H\end{bmatrix}X\begin{bmatrix}D_H^*C_H & B_H^*\end{bmatrix}$$

where $X=\left(I-D_H^*D_H\right)^{-1}$ and:

$$\left[\begin{array}{cc}A_H & B_H\\ C_H & D_H\end{array}\right]= \quad (7)$$

$$\begin{bmatrix}I & 0\\ 0 & \frac{F^{-\frac{1}{4}}}{\sqrt{\beta_i}}\end{bmatrix}\begin{bmatrix}A_M-j\omega_i I & B_M D^{-1}\\ DC_M & DD_M D^{-1}-j\beta_i G\end{bmatrix}\begin{bmatrix}I & 0\\ 0 & \frac{F^{-\frac{1}{4}}}{\sqrt{\beta_i}}\end{bmatrix}$$

Define $\delta_{\omega_{i-}}$ and $\delta_{\omega_{i+}}$ as follows:

$$\begin{aligned}\delta_{\omega_{i-}} &= \max\left\{\lambda\in\Re_-:\det\left(\lambda I+j\boldsymbol{H}\right)=0\right\}\\ &= -\omega_i \text{ if } j\boldsymbol{H} \text{ has no positive real eigenvalue}\\ \delta_{\omega_{i+}} &= \min\left\{\lambda\in\Re_+:\det\left(\lambda I+j\boldsymbol{H}\right)=0\right\}\\ &= \infty \text{ if } j\boldsymbol{H} \text{ has no negative real eigenvalue}\end{aligned}$$

Then condition (6) holds true $\forall\omega\in I(\omega_i)$ where:

$$I(\omega_i)=[\omega_i+\delta_{\omega_{i-}},\omega_i+\delta_{\omega_{i+}}] \quad (8)$$

Proof *Let*

$$H(j\omega)=F(\omega_i)^{-\frac{1}{4}}\left\{\frac{D(\omega_i)M(j(\omega_i+\omega))D(\omega_i)^{-1}}{\beta_i}-jG(\omega_i)\right\}F(\omega_i)^{-\frac{1}{4}}$$

The bounds defining $I(\omega_i)$ are obtained by searching for both positive and negative ω of smallest magnitude such that $I-H(j\omega)^*H(j\omega)$ becomes singular, i.e. $\det\left(I-H(j\omega)^*H(j\omega)\right)=0$. *A state-space representation (A_H,B_H,C_H,D_H) of $H(s)$ is given by equation (7). A state-space representation (A_X,B_X,C_X,D_X) of $I-H(j\omega)^*H(j\omega)$ is then given by:*

$$A_X=\begin{bmatrix}A_H & 0\\ -C_H^*C_H & -A_H^*\end{bmatrix},\quad B_X=\begin{bmatrix}-B_H\\ C_H^*D_H\end{bmatrix}$$

$$C_X=\begin{bmatrix}D_H^*C_H & B_H^*\end{bmatrix},\quad D_X=I-D_H^*D_H$$

Some standard manipulations finally conclude the proof:

$$\begin{aligned}&\det\left(I-H(j\omega)^*H(j\omega)\right)=0\\ \Leftrightarrow\ &\det\left(I+C_X\left(j\omega I-A_X\right)^{-1}B_X D_X^{-1}\right)=0\\ \Leftrightarrow\ &\det\left(I+\left(j\omega I-A_X\right)^{-1}B_X D_X^{-1}C_X\right)=0\\ \Leftrightarrow\ &\det\left(j\omega I-\left(A_X-B_X D_X^{-1}C_X\right)\right)=0\\ \Leftrightarrow\ &\det\left(\omega I+j\boldsymbol{H}\right)=0\end{aligned}$$

In this context, the following algorithm is proposed to compute a guaranteed robustness margin for a high-dimensional uncertain LTI plant [20], [10], [6]. It mainly consists of a repeated treatment on a list of intervals.

Algorithm 1 *(computation of a lower bound on k_{max})*

1 - Initialization:

- *Define an initial value β_{max} for the μ upper bound, either by a μ lower bound computation (see Section Computation of a destabilizing perturbation) or by setting $\beta_{max}=0$.*
- *Define the frequency range $\Omega=[\omega_{min},\omega_{max}]$ on which the μ* upper bound is to be computed. Let $\boldsymbol{I}=\{I_1\}=\{[\omega_{min},\ \omega_{max}]\}$ be the initial list of frequency intervals to be investigated.

2 - While $\boldsymbol{I}\neq\varnothing$, repeat:

- *Choose an interval $I_i\in\boldsymbol{I}$ and a frequency $\omega_i\in I_i$.*
- *Compute β_i, $D(\omega_i)$, $G(\omega_i)$ such that (5) holds.*
- *Set $\beta_i\leftarrow\max\left((1+\varepsilon)\beta_i,\beta_{max}\right)$ and apply Proposition 2 to compute $I(\omega_i)$.*
- *Set $\beta_{max}\leftarrow\beta_i$ and update the intervals in $\boldsymbol{I}$ by eliminating the frequencies contained in $I(\omega_i)$.*

3 - A lower bound on k_{max} is given by $k_{LB}=1/\beta_{max}$.

The proposed algorithm is not based on a frequency grid to be defined a priori, with the risk of missing a critical frequency. On the contrary, it relies on a list of frequency intervals which is updated automatically during the iterations. By this approach, the robustness margin is guaranteed over the whole frequency range and no tricky initialization is required.

Remark 1 *Algorithm 1 can be directly applied to the general case where $\Delta(s)$ is a block-diagonal LTI operator not only composed of real scalars (corresponding to parametric uncertainties), but also of complex scalars and unstructured transfer matrices (representing neglected dynamics).*

Computation of a guaranteed H_∞ performance level

The notion of robust performance is of practical importance. Indeed, it is often desirable to quantify the performance degradations, which are induced by model uncertainties and appear before instability. The following proposition is a direct consequence of the main loop theorem [17] and is used to reformulate the worst-case H_∞ performance problem as a specific skew-μ problem. With reference to figure 2, a fictitious complex block Δ_c is added between the output y and the input e. Its size is to be maximized under the constraint that the interconnection is stable $\forall\Delta \in \boldsymbol{B}_\Delta$.

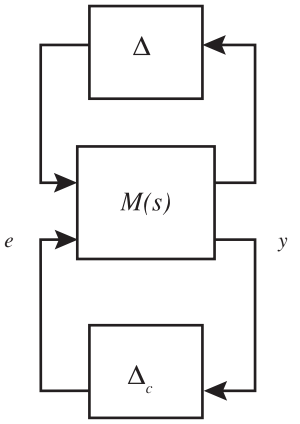

Figure 2 - Augmented system created by addition of a fictitious complex block

Proposition 3 *The following statements are equivalent:*

- $\boldsymbol{F}_u(M(s),\Delta)$ *is stable* $\forall\Delta \in \boldsymbol{B}_\Delta$ *and* $\gamma_{\max} = \max_{\Delta\in\boldsymbol{B}_\Delta} \left\|\boldsymbol{F}_u(M(s),\Delta)\right\|_\infty \leq \gamma$,
- *the size* $\bar{\sigma}(\Delta_c)$ *of the smallest perturbation* $\Delta_c \in C^{p\times p}$ *such that* $\det\left(I - M(j\omega)\operatorname{diag}(\Delta,\Delta_c)\right) = 0$ *for some* $\Delta \in \boldsymbol{B}_\Delta$ *and some* $\omega \in \Re_+$ *is larger than* $1/\gamma$,
- $\mu_{\Delta_a}\left(\operatorname{diag}\left(I_{n,}I_p\sqrt{\gamma}\right)M(j\omega)\operatorname{diag}\left(I_{n,}I_p\sqrt{\gamma}\right)\right) \leq 1, \forall\omega \in \Re_+$, *where* $\Delta_a = \operatorname{diag}\left(\Delta, C^{p\times p}\right)$.

Proof [17]

Similarly to the previous section, μ_{Δ_a} is replaced with its upper bound $\bar{\mu}_{\Delta_a}$. For a given ω_i, the smallest value of γ such that $\mu_{\Delta_a}\left(\operatorname{diag}\left(I_{n,}I_p\sqrt{\gamma}\right)M(j\omega_i)\operatorname{diag}\left(I_{n,}I_p\sqrt{\gamma}\right)\right) < 1$ can then be computed:

- either directly using an LMI characterization [8][9],
- or iteratively using a dichotomy or a fixed-point algorithm together with the formulation (5).

The latter is usually preferred when high-dimensional systems are analyzed, since computational time is much lower. Algorithm 1 (especially step 2b) can thus be slightly modified to compute an upper bound γ_{UB} on the robust H_∞ performance level γ_{max}.

Remark 2 *Algorithm 1 can be further extended to general skew-μ problems, where Δ_c is structured and composed of mixed real/complex uncertainties.*

Worst case analysis

Computation of a destabilizing perturbation

The objective is now to compute an upper bound on $k_{\max}$ to evaluate the conservatism of the lower bound determined in the Computation of a guaranteed stability margin section. This is equivalent to computing a μ lower bound on the whole frequency range. Constructive polynomial-time heuristics exist [24], [21], which provide some worst-case values of Δ. They usually give fast and accurate results when Δ contains some complex uncertainties, but they suffer from two drawbacks. First, convergence problems are often encountered in the purely real case, and the resulting lower bound is then equal to 0. Second, the frequency is fixed. The problem thus has to be solved on a frequency grid, with the risk of missing the most critical parametric configurations even if a fine grid is used. In this context, the key idea of the method described below and initially proposed in [6] is to directly obtain a tight μ lower bound over the whole frequency range rather than at a fixed frequency.

In this perspective, the real μ problem considered in this paper is first regularized by adding a small amount ε of complex uncertainty to each real uncertainty [18]: a perturbation Δ_c is defined with the same structure as Δ, except that the real scalars become complex. The method of [24] or [21] is then applied at a given frequency ω_i, usually with good convergence properties, to the following problem:

$$\begin{aligned} M_a(j\omega_i) &= \begin{bmatrix} M(j\omega_i) & \sqrt{\varepsilon}M(j\omega_i) \\ \sqrt{\varepsilon}M(j\omega_i) & M(j\omega_i) \end{bmatrix} \\ \Delta_a &= \operatorname{diag}(\Delta,\Delta_c) \end{aligned} \tag{9}$$

The resulting μ lower bound is not a lower bound for the original real μ problem: a perturbation $\Delta_a^0 = \operatorname{diag}\left(\Delta^0,\Delta_c^0\right)$ has been obtained, which renders the matrix $I - M_a(j\omega_i)\Delta_a^0$ singular, but it cannot be claimed that $I - M(j\omega_i)\Delta^0$ is itself singular. Nevertheless, if ε is small enough, an eigenvalue λ_0 of the interconnection of figure 1 (left) is usually located near the point $j\omega_i$ of the imaginary axis.

Starting from this good initial guess $\Delta^0 = \operatorname{diag}\left(\delta_1^0 I_{n_1},\ldots,\delta_N^0 I_{n_N}\right)$, the last step is to move λ_0 through the imaginary axis to obtain a destabilizing perturbation for the real μ problem. More precisely, in the spirit of [13], a solution is to introduce an additional perturbation $\tilde{\Delta} = \operatorname{diag}\left(\tilde{\delta}_1 I_{n_1},\ldots,\tilde{\delta}_N I_{n_N}\right)$, which acts as a fictitious feedback gain. The problem is then to find the smallest perturbation $\Delta^0 + \tilde{\Delta}$, which brings the eigenvalue λ_0 on the imaginary axis. As shown in [13], [6], it can be recast as a simple linear programming (LP) problem:

$$\min_{\tilde{\delta}_i} \nu \quad \text{s.t.} \quad \left| \begin{array}{l} -\nu \leq \delta_i^0 + \tilde{\delta}_i \leq \nu \\ \Re\left(\lambda_0 + \sum \alpha_i\tilde{\delta}_i\right) = 0 \end{array} \right. \tag{10}$$

where:

- $\alpha_i = (uB + tD)\dfrac{\partial\Delta}{\partial\delta_i}(Cv + Dw)$
- (A,B,C,D) is a state-space representation of $M(s)$
- u and v are the left and right eigenvectors associated to the eigenvalue λ_0 of the closed-loop matrix $A_0 = A + B\left(I - \Delta^0 D\right)^{-1}\Delta^0 C$,
- $t = uB\left(I - \Delta^0 D\right)^{-1}\Delta^0$ and $w = \left(I - \Delta^0 D\right)^{-1}\Delta^0 Cv$

In the above formulation, the equality constraint means that the real part of λ_0 must be equal to 0 once the additional perturbation $\tilde{\Delta}$ is applied. An upper bound k_{UB} on $k_{\max}$ is obtained as the minimum value of v such that (10) holds.

Note that (10) is a linearized version of the problem to be solved. In practice, it may then be necessary to modify it if λ_0 is not sufficiently close to the imaginary axis. In this case indeed, the accuracy of the first order development may not be sufficient, so as to directly move the eigenvalue onto the imaginary axis. A solution consists in partitioning the real segment which separates λ_0 from the imaginary axis, and to iteratively perform the migration on each sub-segment. More precisely, problem (10) is solved $\boldsymbol{N}$ times, the second constraint being replaced at iteration k with $\Re\left(\lambda_0^k + \sum \alpha_i^k \delta_i^k\right) = \Re\left(\lambda_0\right)\dfrac{\boldsymbol{N}-k}{\boldsymbol{N}}$, where $\lambda_0^k = \lambda_0^{k-1} + \sum \alpha_i^{k-1}\delta_i^{k-1}$ if $k>1$ and $\lambda_0^1 = \lambda_0$ otherwise.

Note that the aim here is not to compute a μ lower bound at a given frequency, but to directly obtain the highest possible lower bound over the whole frequency range as well as the associated frequency ω^*. Indeed, assume that a bound has been computed for the regularized problem at a frequency ω_i, which is far from ω^*. Using the LP method above, the imaginary axis can however be crossed very close to $j\omega^*$, since no constraint is imposed on the imaginary part of λ_0. Such a behavior is generally observed in practice. It is thus sufficient to apply the algorithm on a coarse frequency grid to obtain a tight upper bound on $k_{\max}$.

Remark 3 *The size of Δ_a in equation (9) is twice the size of the initial matrix Δ. But despite this, computing a μ lower bound usually remains much faster than computing a μ upper bound.*

Worst-case H_∞ performance analysis

In the spirit of the μ lower bound algorithm in the previous section, a two-step procedure is implemented at each point ω_i of a rough frequency grid:

- The unit ball $\boldsymbol{B}_\Delta$ is investigated by iteratively:
  - computing the gradient of $\bar{\sigma}\left(\boldsymbol{F}_u\left(M\left(j\omega_i\right),\Delta\right)\right)$,
  - performing a line search to maximize this quantity (which boils down to computing the eigenvalues of a Hamiltonian-like matrix), until the problem is roughly solved at ω_i.
- Using the value of Δ computed at step 1 as an initialization, a quadratic programming problem, which locally maximizes $\bar{\sigma}\left(\boldsymbol{F}_u\left(M\left(j\omega\right),\Delta\right)\right)$ with respect to both Δ and ω, is repeatedly solved until convergence.

A lower bound γ_{LB} of γ_{max} is finally obtained, as well as the associated value $\tilde{\Delta}$ of Δ [19].

Tools extensions

Unstructured margins

Structured robustness analysis considers that the uncertainties' effects on the system's behavior are perfectly identified, which can be unrealistic. It is thus often desirable to compute worst-case unstructured margins (gain, phase, modulus, time-delay) to evaluate the effective robustness of a system. In this perspective, some additional fictitious uncertainties δ_M corresponding to gain, phase, modulus or time-delay variations are introduced either at the input or at the output of the considered open-loop system $\Sigma(s)$, depending on whether input or output margins are to be computed (see figure 3). Note that either SISO or MIMO margins can be evaluated, δ_M containing either one $\left(\delta_M = \mathrm{diag}(1,\ldots,1,\delta_{M,i},1,\ldots,1)\right.$ or several $\left(\delta_M = \mathrm{diag}(\delta_{M,1},\ldots,\delta_{M,q})\right)$ scalar uncertainties. The expression of δ_M,i is given hereafter for each margin:

- gain margin: $\delta_{M,i} = 1+\hat{\delta}_i, \hat{\delta}_i \in \Re$
- modulus margin: $\delta_{M,i} = 1+\hat{\delta}_i, \hat{\delta}_i \in C$
- phase margin: $\delta_{M,i} = e^{j\varphi_i}, \varphi_i \in \Re$
- time-delay margin: $\delta_{M,i} = e^{-\tau_i s}, \tau_i \in \Re_+$

For gain and modulus margins, the expression of $\delta_{M,i}$ is polynomial and can be written directly in linear fractional form. For phase and time-delay margins, the non-rational elements $e^{j\varphi_i}$ and $e^{-\tau_i s}$ must be transformed first in order to write the interconnection of figure 3 as a linear fractional representation similar to the one of figure 1 (left). For this purpose, the phase variation $e^{j\varphi_i}$ is replaced using the bilinear transformation with $(1-j\hat{\delta}_i)/(1+j\hat{\delta}_i)$, where $\hat{\delta}_i \in \Re$.

This new element, similarly to $e^{j\varphi_i}$, has a unitary modulus and its phase variation covers the whole phase range [$-\pi$, π] when $\hat{\delta}_i \in \Re$. For the time-delay margin, the substitution of $e^{-\tau_i s}$ is more delicate because of the Laplace variable s. Nevertheless, it can be replaced by a static rational complex function $f\left(\hat{\delta}_i\right)$, $\hat{\delta}_i \in \Re$, where the variation range of $\hat{\delta}_i$ depends on ω. This dependence can then be treated using some results from [23]. The whole process is detailed in [11].

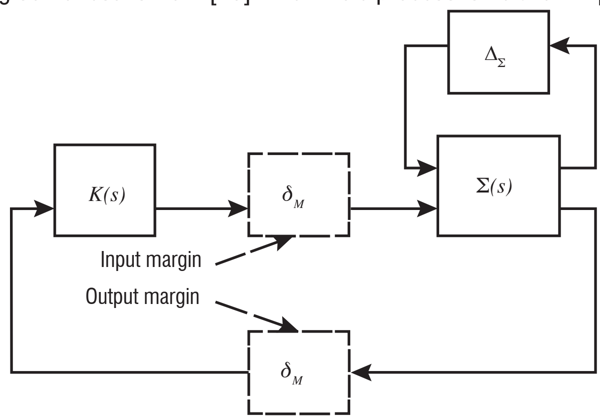

Figure 3 - Introduction of a fictitious uncertainty δ_M

The interconnection of figure 3 can now be written as in figure 1 (left), where Δ contains both Δ_Σ and the $\hat{\delta}_i$. Problem 3 is finally reformulated as follows: assuming that $k_{\max} > 1$, compute the maximum value of the $\hat{\delta}_i$ such that the interconnection between $M(s)$ and Δ is stable $\forall \Delta_\Sigma \in \boldsymbol{B}_{\Delta_\Sigma}$. This is equivalent to a skew-μ problem. Both upper and lower bounds on the various margins can thus be obtained using the algorithms described in the Robustness margins computation and Worst case analysis sections.

Accuracy improvements

Conservatism is defined in this paper as the relative gap η between the lower and the upper bounds on a given quantity x, which can be any of the stability margins or the performance levels considered in the previous sections:

$$\eta = \frac{x_{UB} - x_{LB}}{x_{LB}} \qquad (11)$$

η sometimes reaches unacceptable values, notably in the presence of highly repeated real parametric uncertainties. A well-known technique to ensure that it remains below a specified threshold η_{tol} is to use a branch and bound algorithm [1], [15]. The idea is to partition the real parametric domain into more and more subsets until the relative gap between the highest lower bound and the highest upper bound computed on all of the subsets becomes less than η_{tol}. This algorithm is known to converge for uncertain systems with only real uncertainties [15], *i.e.* conservatism can be reduced to an arbitrarily small value. However, it usually exhibits an exponential growth of computational complexity as a function of the number of real uncertainties. Specifying a threshold η_{tol} is thus used to handle the trade-off between the accuracy of the bounds and the computational time.

Nevertheless, in order to alleviate the computational burden, a strategy based on the progressive validation of the frequency range is proposed here. Assume for example that a subset $\boldsymbol{D}_N$ of the parametric domain and a frequency domain Ω_N are considered at step N of the branch and bound procedure. Algorithm 1 is applied to compute a frequency domain $\Omega_{v,N} \subset \Omega_N$ such that $\det\left(I - M\left(j\omega_i\right)\Delta\right) \neq 0$ holds $\forall \Delta \in \boldsymbol{D}_N$ and $\forall \omega \in \Omega_{v,N}$. During the next step, the analysis performed on each subset of $\boldsymbol{D}_N$ then only considers the frequencies in Ω_N which have not been validated at step N, *i.e.* which are not contained in $\Omega_{v,N}$. Consequently, after a few steps, the analysis is only restricted to very narrow frequency intervals corresponding to critical frequencies. This results in a drastic reduction of the computational load induced by a classical branch and bound procedure.

Application to flight control laws validation

The algorithms described in the previous sections are now evaluated on a realistic application. All calculations are performed on a 3GHz PC with 3GB RAM.

Description of the model

A high fidelity model composed of 22 states is considered here. It describes both the rigid and the flexible closed-loop longitudinal dynamics of a civilian passenger aircraft. It is parameterized by 4 real parameters characterizing the aircraft's mass configuration: center and outer tanks filling levels δ_{CT} and δ_{OT}, embarked payload δ_{PL} and position of the center of gravity δ_{CG}. The model is written in linear fractional form as shown in figure 1 using the LFR Toolbox for Matlab [12]. As the effects of the parameters on the system behavior are modeled very accurately, the size of Δ is quite large:

$$\Delta = \mathrm{diag}\left(\delta_{CT} I_{48}, \delta_{OT} I_{28}, \delta_{PL} I_{15}, \delta_{CG} I_4\right)$$

Δ is normalized, which means that the whole parametric domain is covered when Δ takes all possible values in $\boldsymbol{B}_\Delta$.

Robust stability analysis

Robust stability is first analyzed in order to check whether stability can be guaranteed over the whole parametric domain. For this purpose, several μ upper and lower bounds are computed, and the results are illustrated in figure 4. The bounds are first computed without branch and bound. A relative gap of about 40% is obtained and the computational time is very reasonable considering the large size of the model. Nevertheless, robust stability cannot be guaranteed over the whole parametric domain, since the upper bound is larger than 1. Much better results are obtained with the branch and bound algorithm, since robust stability can be guaranteed as soon as η_{tol} is less than 15%. Moreover, the additional computational cost induced by the use of branch and bound is quite low thanks to the efficient strategy introduced before used to progressively validate the frequency domain (see Section Accuracy improvements). Note that all μ upper and lower bounds are computed using the algorithms described in Sections Computation of a guaranteed stability margin and Computation of a destabilizing perturbation respectively. Thus, the only tuning parameter in this stability analysis is the threshold η_{tol}.

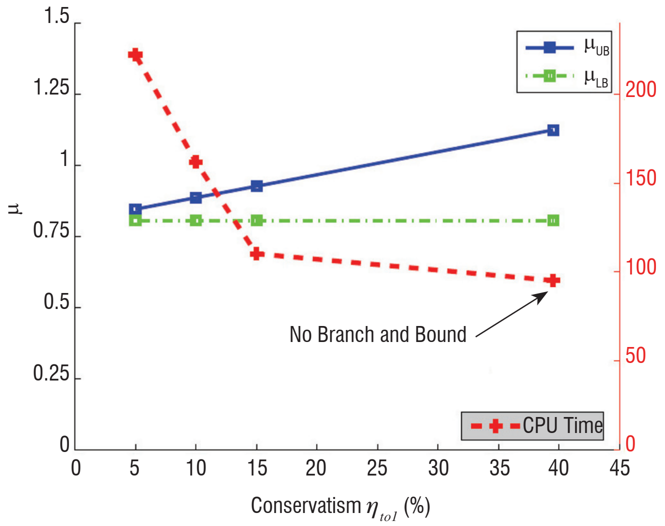

Figure 4 - μ bounds and CPU time versus conservatism

Worst-case H_∞ performance analysis

Worst-case H_∞ performance is evaluated for the transfer function between the vertical wind velocity and the vertical load factor. In order to identify the secondary peaks of the frequency response, the analysis is performed on three contiguous frequency intervals. A skew-μ problem is thus solved on each one of these intervals. Figure 5 shows the bounds on $\gamma_{\max}$ obtained with $\eta_{tol} = 20\%$ as well as the frequency responses of the uncertain system computed on a fine parametric grid. Results are very accurate.

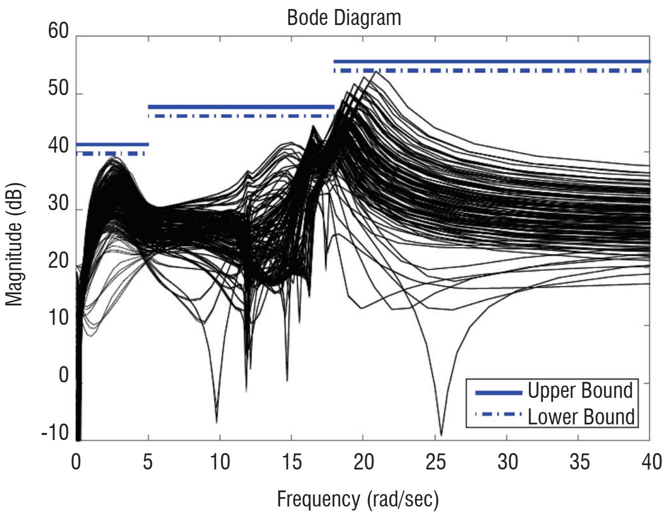

Figure 5 - Bounds on $\gamma_{\max}$ and frequency responses on a fine parametric grid

Worst-case unstructured margins

Worst-case SISO unstructured margins are finally computed. With reference to figure 3, the open-loop system $\Sigma(s)$ is composed of actuators, open-loop aircraft and sensors models in a feedback loop with a dynamic controller K(s). The input of $\Sigma(s)$ is the elevator deflection, while the outputs are the pitch rate and the vertical load factor. Figure 6 shows the bounds on the gain, modulus and phase margins obtained with $\eta_{tol} = 25\%$, and the Nyquist responses of the uncertain system on a fine parametric grid. Once again, results are quite satisfactory and conservatism is efficiently mastered.

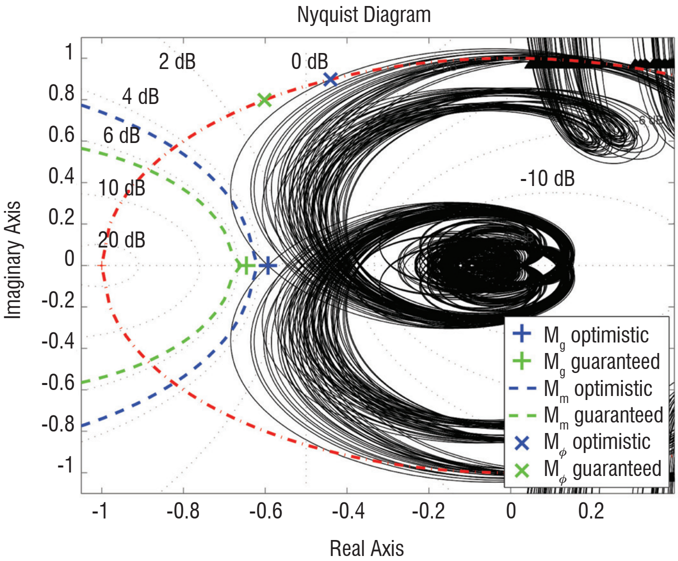

Figure 6 - Upper (optimistic) and lower (guaranteed) bounds on the worst case gain (M_g), modulus (M_m) and phase (M_φ) margins and Nyquist responses on a fine parametric grid

Conclusion and prospects

Several μ-analysis based tools developed by the systems control group of Onera are reviewed in this paper. They are used to compute both upper and lower bounds on the robust stability margin, the worst-case H_∞ performance level, as well as the worst-case gain, phase, modulus and time-delay margins. Unlike most existing methods, these bounds are guaranteed over the whole frequency range, and not only on a finite frequency grid. Moreover, an efficient branch and bound scheme can be used to obtain bounds with the desired accuracy, while still guaranteeing a reasonable computational complexity. These algorithms which will form the basis of a next release of the Skew Mu Toolbox for Matlab [7] should enable to considerably improve the flight control systems validation process in the near future

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Acronyms

SOS (Sum Of Square)
IQC (Integral Quadratic Constraint)
LTI (Linear Time Invariant)
MIMO (Multi-Inputs Multi-Outputs)
LFR (Linear Fractional Representation)

Clément Roos holds a PhD in Automatic Control from Supaero, for which he received two awards. He often takes part in industrial projects with Airbus and Dassault, and was involved in the european projects GARTEUR-AG17 and COFCLUO. His research interests focus on LFT modeling, robustness analysis and nonlinear (especially anti-windup) design. He is the author or co-author of several journal and conference papers, as well as a few book chapters.

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An Overview of Relevant Issues for Aircraft Model Identification

A number of activities in aeronautical engineering rely on the availability of models to represent the real behavior of the aircraft. Let us quote, for example, the development of autopilots and synthesis of flight control laws, the study of the handling qualities, the fault monitoring process, the prediction of hazardous behaviors, or the implementation of simulators used to train the pilots and to validate hardware and software systems. The initial modeling derived from CFD, wind tunnel or ground tests is seldom reliable enough with respect to the requirements. Hence, the needed accuracy is finally achieved thanks to suitable identification techniques and to a set of peculiar flight tests. In addition, the complexity of the models has increased in recent years, along with more stringent accuracy requirements to satisfy the raising constraints of the new aeronautical devices which make use of these models; *e.g.*, an increasing number of vibration modes in the low frequency range for flexible aircraft, or a larger complexity and non-linearity of the aerodynamical models in the rigid case. Hence, the variety of problems and models under consideration entails taking an interest in a wide range of identification techniques. These include basic methods, like least-squares or maximum likelihood and their variants, spectral analysis and estimators based on Kalman filtering, as well as more recent approaches like neural-based or subspace methods. Special care is given to the frequency domain formulation of the algorithms, especially in the flexible A/C case. Most of these methods are not directly usable as they are and need to be adapted to the peculiarities of aeronautics. Accordingly, this paper reviews the various issues related to the identification process when applied to such applications. These steps include data pre-processing, input design, time vs. frequency domain methods, model validation, etc., and are illustrated by industrial problems dealt with by Onera, for rigid as well as for flexible A/C modeling.

Introduction

The concept of model identification refers to a set of tasks required to determine, and then to tune, a suitable modeling, likely to explain the experimental behavior of a given system. This involves choosing the type of mathematical relationships linking the i/o observed variables (often denoted as structural identification), as well as adjusting the unknown parameters of these equations (denoted as parametric identification). The early developments in system identification date back to the seventies, but this topic remains the subject of new developments nowadays, especially for aeronautics. In this domain, the works concern the modeling of both rigid aircraft, described by the flight mechanics equations, and flexible aircraft where the structural deformations are taken into account.

A number of activities in aeronautical engineering rely on the availability of models to represent the real behavior of the aircraft. Let us quote for example the development of autopilots and the synthesis of flight control laws, the study of the handling qualities, the fault monitoring process, the prediction of hazardous behaviors, or the implementation of simulators used to train the pilots and to validate hardware and software systems. The initial modeling, obtained from Computational Fluid Dynamics, wind tunnel or ground tests, is seldom accurate enough with respect to the accuracy requirements. Hence, this accuracy is finally achieved thanks to suitable identification techniques and to a set of peculiar flight tests. Models have become increasingly complex in recent years, and there are more stringent accuracy requirements to satisfy the raising constraints of the new aeronautical devices which make use of these models. In the framework of flexible aircraft for example, the new materials and the structural alleviation lead to an increasing number of vibration modes in the low frequency range, some of which are likely to interact with the rigid body modes. The identification of a flexible model, or even of a coupled one representing both the rigid and flexible components, thus becomes a much trickier task but is also more crucial than it was in the past. On the other hand, the aerodynamical models used for the rigid case are also becoming drastically complex since from now on they integrate several effects that were disregarded before, or simply because the airplanes themselves have become much more complicated. Let us quote A400M as an example, or A380 with an unprecedented proliferation of the control surfaces. We also need to point out a strong industrial constraint, which affects the identification process; the need to reduce the duration and cost of the identification tests, taking place during the first flights of a new airplane (both of these being significant), requires specific techniques to design and then to process this type of tests to be developed, without degrading the quality of the resulting models.

One feature of the aeronautical domain is that we can rely on many physical models derived from aerodynamics, structural dynamics or flight mechanics. Quite often however, these models cannot be implemented into identification algorithms just as they are, because of high orders or strongly nonlinear behaviors. Hence, they require grey-box type simplified physical representations to be developed, or even to make use of intermediate black-box models, linear or nonlinear types. *E.g.*, these submodels facilitate the modeling of multimensional aerodynamic nonlinearities, usually complex and poorly structured, and are also beneficial to the linear modeling of A/C aeroelastic behavior by means of polynomial transfer functions in the Frequency Domain (FD). In addition, some constraints should be respected during the process: the aircraft simulation will require continuous-time differential equations to be integrated, *a priori* knowledge about the predicted A/C behavior should be considered, a physical understanding and interpretation of the results will remain mandatory and could induce additional constraints in the optimization process.

The variety of problems and models under consideration entails having a wide range of identification techniques available. Obviously, they include basic methods, such as least-squares or maximum likelihood (ML) and their variants, spectral analysis and estimators based on Kalman filtering (KF), as well as more recent approaches like neural or subspace methods. Special care is given to the FD formulation of the algorithms, especially in the flexible A/C case; working inside a limited frequency band allows a good part of the noise to be cancelled and the computational cost to be decreased noticeably, thanks to information compression. Most of these methods are not directly usable as they are and need to be adapted to the peculiarities of aeronautical problems (previously mentioned). For example, a very restrictive point comes from the requirement of coupling identification tools with industrial simulators, in order to enable model updating and to facilitate the implementation of the results. This is all the more restrictive because the simulators also suffer from increasing complexity, involving a drift of the computational costs which is hardly compatible with the number of simulations required by the identification procedure. Another major concern arises from the will to automate and systematize the test processing, in order to reduce its duration and to facilitate its progress. Indeed, the whole set of available flight tests represents a huge amount of data and hence some semi-manual steps of the process are especially tedious for the engineers responsible for sifting through the data. Automation also enables a global and joint processing of many tests, as well as the gradual introduction of new tests as they become available. For the flutter analysis of flexible A/C, a near real-time processing is considered to open the flight envelope and again it results in strong constraints on the performances and the features of the tools to be developed.

On the other hand, the accuracy of the estimates issued from the identification algorithms is highly dependent on the frequency content of the input signals used to excite the system, in addition to the quality of the measurements which can be degraded by several types of errors (incorrect alignments, drifts, delays, calibration errors, etc.) superimposed on the usual noises and external disturbances (wind, turbulence). Even if the signal-to-noise ratio is satisfactory, an improvement can be achieved by taking advantage of the redundancy that usually exists between some of the available measurements (especially with aircraft instrumented for flight testing). Regarding the excitation signals, the common idea consists in looking for optimal inputs permitting the estimation accuracy to be improved, this optimization taking place by considering either single tests or multiple tests. This question can also be extended to minimizing the signals length while keeping a given level of accuracy, or even generalized to other types of criteria.

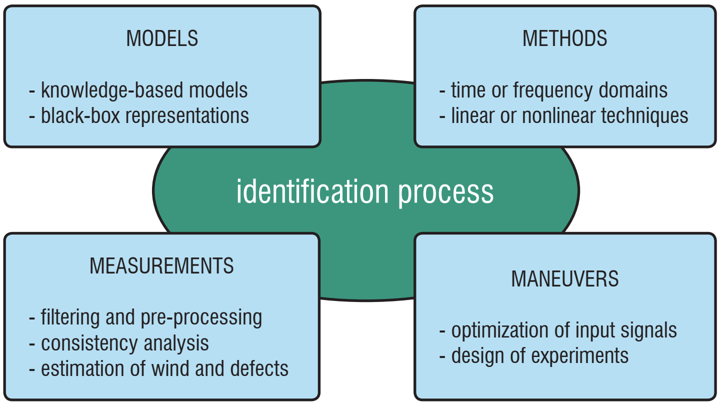


Figure 1 – Identification process and the *Quad-M* basics

To sum up, it appears that identification in aeronautics calls for various skills: flight mechanics, aerodynamics, structural dynamics, signal processing, estimation and optimization techniques. Their combination is absolutely mandatory to obtain a relevant model, in fine. These various aspects are depicted by the scheme in figure 1, which stresses that the identification process is located at the meeting point of the *Quad-M* basics (*Maneuvers-Measurements-Models-Methods*) [14]. These will be detailed in the following sections and illustrated by a set of industrial applications resulting from Onera's activities in this field.

State-of-the-art and industrial context at Onera

Owing to its positioning and to its mission, Onera plays an intermediate role between academy and its main industrial partners. Within the framework of identification, as in others domains, this role presupposes that new promising methods will be investigated, adapted and transposed whenever necessary, and will finally be evaluated through aeronautical applications. Since the early historical works of Landau [10], De Larminat [8] and Richalet *et al.* [51,55] in the seventies, the academic research in this domain has been active in France. Without claiming to be exhaustive in any way, several university specialists, such as E. Walter [75] and A. Benveniste [45] contributed especially to developing and promoting new techniques. In Europe, the Delft University of Technology also became renowned in the identification domain [50,72,74], as well as the Vrije Universiteit of Brussels [59] for modal estimation, without forgetting L. Ljung, one of the most famous European specialists in this topic [38]. With regard to aeronautical applications, the key players are obviously not so many; let us mention R. Jategaonkar at the DLR [24-26] and the E. Morelli/V. Klein [29,46-48] and R.E. Maine/K.W. Iliff pairs at NASA [41-43], two organizations that have a scientific scope and authority to perform activities similar to those of Onera.

System identification was a very first activity for the Systems Control and Flight Dynamics Department (DCSD) of Onera. DCSD has been developing and implementing identification techniques since the beginning of the seventies [31,32] in various application fields, such as: industrial processes, robotics, marine and aerial vehicles. It is noteworthy that some of these methods can benefit more than one domain and that advances can often be transposed to other applications. For instance, the experience gained and strengthened in the aeronautical domain through airplanes and helicopters has allowed DCSD to identify many warships and submarines from sea tests (linear and nonlinear models), as required by the synthesis of their control laws [15,17]. Parallel to the aeronautical sector, this activity has represented a major area of application for Onera from the beginning of the eighties since, for 25 years, the autopilots of most French submarines, frigates and aircraft carrier were studied and carried out by DCSD. Besides these historical works, which lie beyond Onera's usual scope, DCSD has been working with French aircraft manufacturers (Airbus and Dassault Aviation) on the whole spectrum of themes presented in the introduction, applying them through a succession of industrial programs: from the A320 to the A380, the Rafale, UAVs, etc. Let us mention very briefly:

• A close cooperation with the Flight Mechanics and Simulation Department of Airbus has been running without a break for about 30 years and has led to the implementation of several software in its identification tool unit for an operational use [37]. It is continuing nowadays through research programs aimed at improving the industrial process that allows the aerodynamic model to fit in the flight envelope as a whole. Indeed, the aerodynamic forces appear in the flight mechanics equations as nonlinear look-up tables depending on a number of variables (Mach number, angles of attack (AoA) and sideslip, configuration, dynamic pressure, etc.). Consequently, the identification task can be performed either within a linear (or weakly nonlinear) framework by processing only tests performed under similar flight conditions, or within a fully nonlinear framework by seeking to adjust the global modeling in an extended area of the flight domain.

• The transposition of some techniques developed for the civilian industry to military aircraft and drones was also considered a few years ago, during research programs involving Dassault Aviation. This work was intended to automate the industrial processes for identifying the models of new aircraft, a tedious task considering all of the load configurations. Appropriate techniques, suitable for dealing with unstable models (linear or nonlinear), were developed and evaluated from real flight data.

• The processing of the flight test campaign for flutter analysis is the subject of a cooperation with the Flight Tests Department of Airbus, which dates back to the mid-eighties and which has made progress in successive stages through more and more ambitious goals [64-71]: SISO identification at first, then SIMO (Single Input-Multiple Outputs) implementation within the framework of the MEFAS project in the early 2000 s [57], and finally MIMO processing in the FIND project which is still underway. Hence, the real-time performance of DCSD approaches remains very competitive in comparison to other commercial products, such as the polyMAX method developed by the company LMS. As such, Onera was also involved in the European project FLITE2 which gathered many specialists in modal analysis (French, Belgian and Polish universities, laboratories), together with Airbus and Dassault Aviation. DCSD managed the working group TRAMPOLINE, which studied the continuous tracking of aeroelastic modes during the acceleration stages between two flight conditions.

Input design and flight test optimization

Off-line techniques

Flight test protocols

As numerical simulation becomes widely used in aeronautics, the requirements regarding the accuracy and reliability of the flight dynamics models are increasing. To improve the representativeness of the models, flight test protocols are thus designed and flown to adjust some relevant coefficients of the predicted aerodynamic model to the real aircraft. However, the permanent concern of building more accurate models in a shorter time leads to this identification process being revisited, by designing optimal inputs. Such an optimization belongs to the field of Experimental Design (ED), which is basically aimed at defining experiments suitable for the modeling purpose. In our context, an experimental protocol gathering several input signals can thus be mathematically represented as:

$$\Xi = \left\{ \left(N_T, u^i(t) \right) \big/ N_T \in N^*, i = 1 \ldots N_T \text{ and } t \in [0, T_i] \right\} \tag{1}$$

In (1), N_T corresponds to the total number of aircraft flight test maneuvers considered for aerodynamic parameter estimation, and the index i denotes the current maneuver with time duration T_i. The input vector $\mathrm{u}^i(t)$ associated with the i^{th} flight test can be either a single or a multiple control surface input signal. Optimal ED can thus be performed on the basis of criteria that characterize the uncertainty in the model parameters to be estimated, denoted by θ. Such cost functions depend on the estimator used to conduct the identification process. In particular, for any asymptotically unbiased and efficient estimator, a minimum achievable parameter standard deviation, also called Cramer-Rao lower bound [41], can be computed for each component of the vector θ. The problem of ED can thus be formulated as follows:

$$\begin{aligned}
&\text{Given}: \Xi = \left\{ \left(N_T, u^i(t) \right) \big/ N_T \in N^*, i = 1 \ldots N_T \text{ and } t \in [0, T_i] \right\} \\
&\text{Find}: \Xi^* = \left(u^1(t) \quad \cdots \quad u^i(t) \quad \cdots \quad u^{N_T}(t) \right)^* = \underset{\Xi}{\operatorname{argopt}} \left(J(\Xi) \right) \\
&\text{Subject to}: \forall i = 1 \ldots N_T, \forall t \in [0, T_i] \begin{cases} \forall j = 1 \ldots n_u, & \Gamma_j(u^i(t)) \le \gamma_j(t) \\ \forall k = 1 \ldots n_y, & \Lambda_k(y^i(t)) \le \lambda_k(t) \end{cases}
\end{aligned} \tag{2}$$

In (2), integer n_u (resp. n_y) corresponds to the number of non-linear constraints (Γ, γ) (resp. (Λ, λ)) that the inputs (resp. outputs) must satisfy in the design process due to flight tests safety: inputs energy, A/C loads tolerance, sideslip angle limitations… In problem statement (2), criterion J can take, among other possibilities, the form of a non-linear scalar function applied to the Fisher information matrix F, s.t. $J(\Xi) = \Phi(F(\Xi,\theta)) \in \mathcal{R}$. F is calculated from the matrix of the model output sensitivities $S(t)$ to the parameter vector θ s.t.:

$$F(\Xi,\hat{\theta}) = \sum_{i=1}^{N_T} \frac{1}{np(i)} \sum_{j=1}^{np(i)} S^T(t_j,u^i(t_j))\, R^{-1}\, S(t_j,u^i(t_j))$$
$$\text{where } S(t_j) = \left.\frac{\partial y(t_j,u^i(t_j))}{\partial \theta}\right|_{\theta=\hat{\theta}} \tag{3}$$

In (3), $y(t)$ designates the outputs of the simulation model and the weighting factors $\text{np}(i) \in \mathcal{N}^*$ the number of measurement points available per flight test. R is a diagonal weighting matrix. An illustrative and general class of functions Φ is given by the following family ($k \in \mathcal{N}^*$):

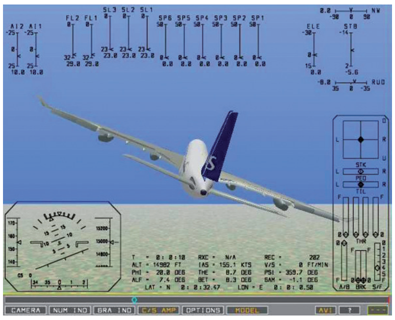
$$\Phi_k(F(\Xi,\theta)) = [\frac{1}{p}\text{trace } (QF^{-1}(\Xi,\theta)Q^T)^k]^{\frac{1}{k}}$$
$$\text{if } \det(F(\Xi,\theta)) \neq 0 \quad (+\infty \text{ otherwise}) \tag{4}$$

where Q is also a weighting matrix. Other examples based on the mathematical notions introduced in equation (3) and commonly used in the literature are given by:

- $\text{trace}(F)$ which represents the amount of information available through the set of flight tests, but does not take into account the possible correlations between the effects;
- $\log(\det(F))$ which is indicative of the global sensitivities of model outputs towards the aerodynamic parameters, collected for a given set of flight tests. Inputs that maximize this scalar norm are called D-optimal;
- $\text{trace}(F^{-1})$ which is equal to the sum of the variances of the parameter estimation errors. Inputs that minimize this criterion are called A-optimal;
- $\lambda_{\max}$ of F^{-1} which is equal to the maximum radius of the uncertainty ellipsoid. Inputs that minimize the greater eigenvalue of the dispersion matrix are called E-optimal.

As shown in (3)-(4), the objective function depends on θ which are unknown parameters. More general mathematical formulations (*e.g.*, based on the expectation) can be used to introduce some given uncertainties on these parameter values. More details are available in [75] (see robust optimal experiment design). When the number of experiments N_T is fixed *a priori*, the ED formulation (2) is reduced to an Optimal Input Design (OID) issue, which is unfortunately an infinite dimensional problem since $\text{U} = \{\text{u}^i(t)/i = 1 \dots N_T\}$ are functional decision variables. Consequently, solving OID requires an approximation by a finite dimensional problem using a non-linear programming approach. Input signals U of Ξ are thus parameterized in order to conduct a non-linear optimization. Despite this approximation, the resulting OID problem remains difficult to solve due to its global feature. Indeed, several approaches corresponding to various levels of complexity exist to tackle issue formulation (2). For instance, the OID problem can be solved on the basis of a single flight test ($N_T = 1$), for which an optimal scalar input signal, applied to only one A/C control surface, is desired ($\dim(\text{u}^1)* = 1$). On the contrary, the same issue can be tackled globally, considering a set of flight tests ($N_T > 1$) composed of both mono and multi-dimensional input vectors, which results in a problem that is far more complex to solve than the previous one.

The state of the art in the field of OID dedicated to parameter estimation points out the Time Domain (TD) methodology developed by Klein/Morelli, which applies the principles of dynamic programming (see [46-48]), as the main contribution. A literature review shows that other methods exist, such as the minimum flight test length via optimal inputs developed by Chen, which applies the principles of the time-optimal control theory [5]; let us also quote the FD OID methodologies initially set by Mehra [44], and then generalized by Mulder [50], in which input signals are parameterized from a predefined basis of orthonormal functions. Yet, none of these seems fully suitable for tackling and solving the OID problem (2) in its entirety (*i.e.* multiple flight tests with multidimensional input signals). This observation has motivated the development of new methodologies based on the theoretical principles of Evolutionary Computation (EC) to solve formulation (2) in various frameworks (single/multiple input signals for single/multiple experiments). The optimization techniques used correspond to original adaptations of the genetic and particle swarm optimization algorithms, for handling both continuous and discrete decision variables. Theoretical details of these methods are available in [60,61]. Among other capabilities, the resulting OID algorithms permit *a priori* information, defined through usual reference flight tests so that expert know-how can be preserved for flight dynamics identification, to be integrated into the optimization process. The results obtained show promising gains in both the global flight test duration and the accuracy of the estimated parameter. ED and OID methodologies are now entered into a phase of validation in flight. A series of flight tests has been flown to validate the theoretical results obtained in simulation. The objective is to prove that this kind of new input signals is able to provide at least the same level of parameter accuracy as in the usual flight test protocols, while significantly reducing the overall length of the flight tests. Video 1 illustrates a typical example of optimized input signals, simulated on an AIRBUS A340/300 and used for the identification of the lateral flight dynamics.



Video 1- Optimization of input signals for an A340/300

Video - http://www.aerospacelab-journal.org/al4/relevant-issues-for-aircraft-model-identification

Definition of excitation signals for aeroelastic mode estimation

Flutter is a divergent aeroelastic phenomenon, usually resulting from a coupling between flexible modes. Hence, it is mandatory for certification to prove that the aircraft is free from flutter throughout the flight domain. For this purpose, the flight test strategy consists in applying excitations to the aircraft structure by means of the control surfaces, at stabilized flight conditions (constant speed and Mach number). Acceleration measurements are then used to analyze the evolution of aeroelastic modes. Clearance for the next flight condition is given if it is satisfactory and safe. Flutter tests are usually performed by using two types of excitation signals: sine sweeps and pulses. The former provides a good excitation level over a prescribed frequency range, but it is also very time-consuming (nearly 120 s long). For this reason, pulse excitation signals (see figure 2) are preferred nowadays, since they result in shorter duration tests (the useful response is usually 10 s or 15 s long).

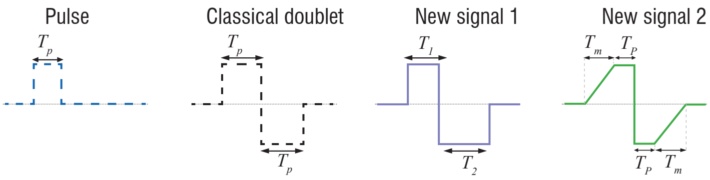


Figure 2 – Shape of classical vs. innovative excitation signals

However, the excitation level provided by this kind of signal is lower than that provided by sine sweeps, and the frequency range is also limited. Research has been performed at Onera for defining better excitation signals. Two innovative orientations were studied in order to improve the quality of the modal analysis and to reduce the test duration in the meantime.

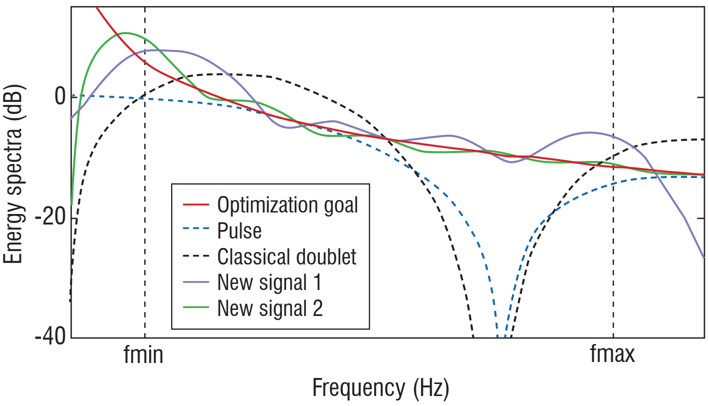
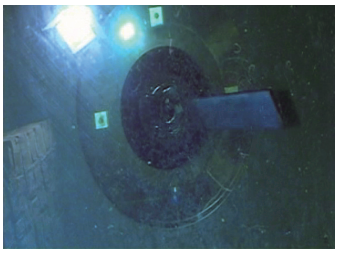


Figure 3 – Spectral comparison of classical and innovative excitation signals

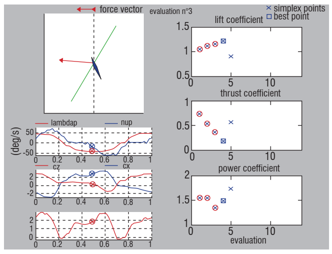
A first approach deals with the distribution of the excitation signal through the control surfaces. Instead of applying signals through pairs of control surfaces, the idea is to combine the excitations applied to the whole set of control surfaces at the same time. Thus, more energy is introduced into the structure. The deflections of the surfaces are also coordinated, so as to excite the A/C modes more efficiently [22,70]. A second approach focuses on the design of more efficient excitation signals. The objective is to devise signals as simple as possible, with a duration comparable to pulses but with an improved frequency content [71]. This is illustrated in figure 3, where the spectra of the 4 excitation signals plotted in figure 2 are depicted. We can notice a gap in the spectra of the conventional and pulse doublet. Conversely, the 2 new signals proposed do not present any weaknesses in the whole frequency band of interest.

On-line techniques

In 2002, Onera launched an internal research program called REMANTA (*REsearch program on Micro Aerial vehicle and New Technologies Application*) on biologically-inspired Micro Air Vehicles [40], which was aimed at improving scientific and technical knowledge in several topics, such as unsteady aerodynamics, actuation, structural dynamics and control. In order to gain a better understanding of specific unstationary aerodynamic phenomena at low Reynolds numbers, experimental tests were carried out in the Onera/DAAP hydrodynamic tank, with a scaled wing model flapping in water, in order to maintain the Reynolds similitude (see video 2).



Video 2 - Experiments in a hydrodynamic tank
Video - http://www.aerospacelab-journal.org/al4/relevant-issues-for-aircraft-model-identification



Video 3 - Optimization of wing motion
Video -http://www.aerospacelab-journal.org/al4/relevant-issues-for-aircraft-model-identification

A specific experimental set-up was designed to analyze hovering flight which requires large angular motions, and an innovative on-line optimization process was proposed to seek efficient wing kinematics without needing a preliminary identification of the flight dynamics model [54]. The experiment consists in a rigid up-scaled wing and in a mechanism including two independent servo-controlled motors to control the flapping and pitching motions. The search for efficient wing kinematics consists in an optimal input design problem with the experimental set-up in the loop. A parameter optimization technique was implemented to determine the shapes of a periodic wing motion maximizing the performance criteria computed from force balance measurements (figure 4).

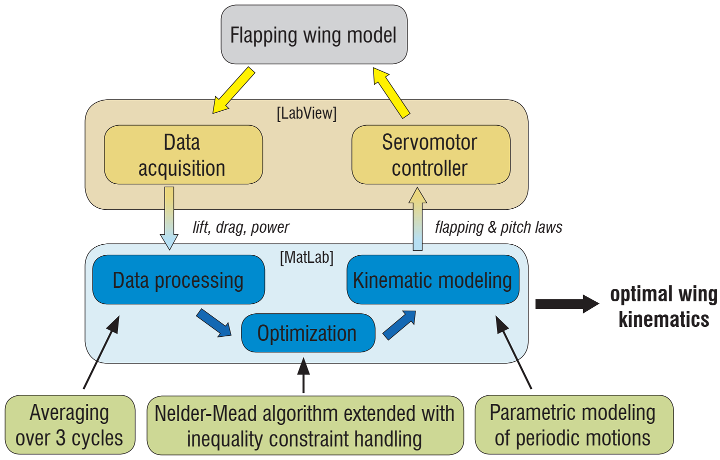


Figure 4 – On-line optimization process of wing kinematics

The two periodic laws involved in wing motions have been modeled in a parametric form, chosen to represent various wing kinematics observed in the literature review [53], with a limited number of parameters (figure 5).

The flapping model consists of four 3rd order polynomial arcs. Signal shape is defined by tb and pb values. The duty cycle parameter rb can be modified to deliver dissymmetrical signals. The adjustment of only one parameter facilitates the reproduction of periodic functions continuously varying from square to triangular shapes, as well as cosine functions. The pitch motion model involves 3 parameters. Mathematical functions were established to reproduce insect wing kinematics, which corresponds to a nearly constant incidence during wing stroke [54].

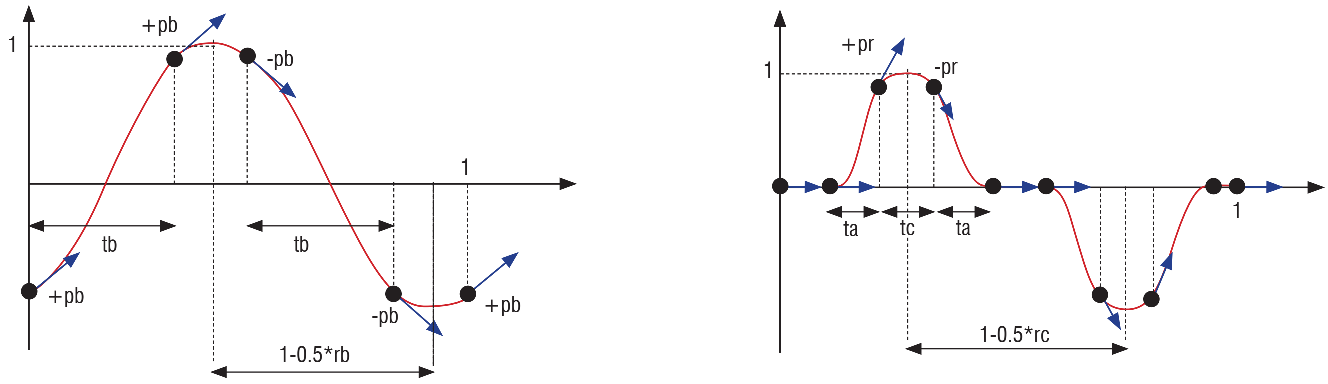


Figure 5 – Modeling of flapping angle (left) and pitching rate (right)

A direct search method based on the Nelder-Mead algorithm was implemented to optimize the parameters of the flapping laws. This algorithm, which does not require gradient evaluation, is well suited to avoid the effects of measurement noise on the approximation of gradients by finite-difference [2]. This method, which is an extension of the original simplex method, is based on a comparison of the criteria at the vertices of a simplex. The algorithm combines three geometric operations (reflection, expansion and contraction) in order to construct a new simplex in a favorable direction. This is a simple, intuitive and relatively stable method that is used in various domains and is renowned as a computationally efficient algorithm to minimize noisy unconstrained functions. The algorithm requires the choice of an initial point, which was set here to kinematics optimized by using an *a priori* simulation model. Classical convergence criteria have been supplemented with detection of simplex degeneracy. The original algorithm was extended to handle bounded parameters and nonlinear inequality constraints. Constraints are accounted for by an adaptive penalization approach and a technique robust to the initialization of the penalty parameters.

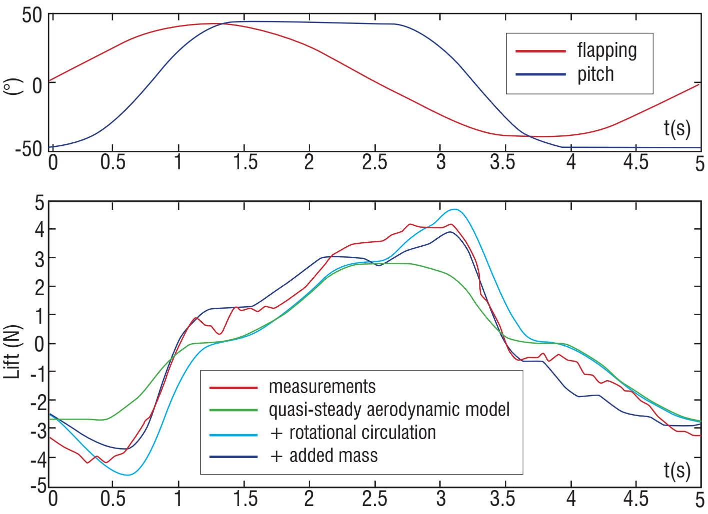


Figure 6 – Time history of computed and experimental forces

During the first test program, a restricted set of parameters was tuned in several configurations, resulting in the optimization of:

- pitch shape with a sine flapping in a horizontal stroke plane, in order to maximize the mean lift coefficient;
- flapping and pitch shapes in a horizontal stroke plane, to minimize the mean power for a minimum mean lift coefficient;
- pitch shape with a sine flapping in an inclined stroke plane, to maximize the mean lift coefficient (see video3).

The preliminary analysis of the test results shows a fast convergence of the iterative optimization process and an optimal kinematics shape close to those obtained with the *a priori* simulation model. Hydrodynamic force measurements were analyzed to improve the reliability of the simulation model, based on a simplified aerodynamic model consisting of a single-element model. Adjustments to the lift gradient coefficient, and to the location of the reference point on the wing chord used for the computation of the local AoA, lead to a good match for instant lift forces over a complete cycle. Figure 6 presents the contribution of separate components of the aerodynamic model (from green, to cyan, to blue colors). In the same way, the aerodynamic moments resulting from the global forces applied to the aerodynamic center match well with the time history of the three components (figure 7). Further experimental tests should be performed to complete the validation of this on-line optimization process, with more complex wing kinematics and multi-objective optimization methods, for hovering and forward flight.

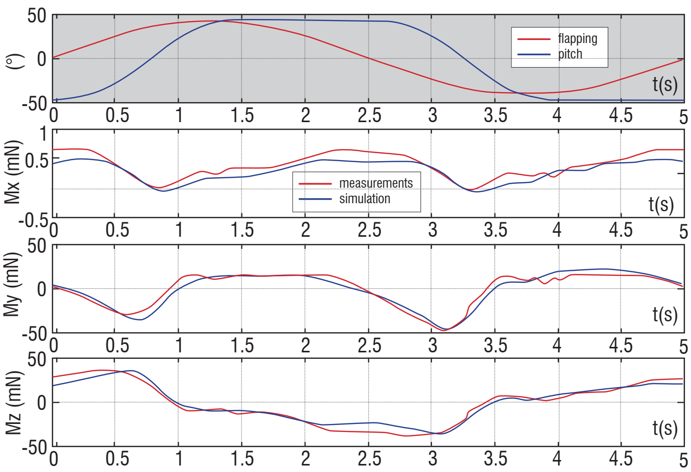


Figure 7 – Time history of computed and experimental moments

Data Pre-Processing And Consistency Analysis

Consistency analysis

The development of a new airplane involves a series of flight tests intended to update and validate the aircraft model, especially used for flight control design and for training simulators. The goal of these tests is to ensure an accurate representation of the aircraft behavior over its whole flight envelope, but also in ground to flight transitions. The accuracy of the updated model strongly depends on the quality and consistency of the measurements recorded during the flight tests. This data often contains deficiencies such as biases, time delays and air data calibration errors, which must be estimated before undertaking the A/C identification process. Furthermore, wind components can only be partially reconstructed from the comparison between ground speed and air speed measurements. Accurate and reliable measurements of ground velocities are achievable by using DGPS devices. On the other hand, air data information is corrupted, especially in ground effects, by aerodynamic disturbances that are only partially corrected by calibration laws.

With the aim of achieving a systematic check of data consistency, a set of estimation tools based on KF and Rauch smoothing techniques has been developed by DCSD. These tools are designed from simple physical models (kinematics, atmosphere), independent from the aircraft modeling which is not accurate as yet at this stage. Experience has proven that an incomplete or imperfect modeling can induce disturbances in a set of variables and moreover can complicate the interpretation of anomalies. To avoid these drawbacks, a multistep checking process has been developed on the basis of models of increasing complexity. This multistep procedure enables an easy detection and localization of some unexpected errors, for example the reference position of the velocity measurements. Flight data analysis is performed in three stages, involving a consistency checking of:

- Angular data: This estimator is also relevant for estimating the angular accelerations, which are useful to update the aircraft model thanks to an equation error approach (EE);
- Ground speed: DGPS velocities are compared to the velocities resulting from the integration of the accelerometers and previously validated angular measurements;
- Air data: Wind is estimated from the difference between the ground and air velocities.

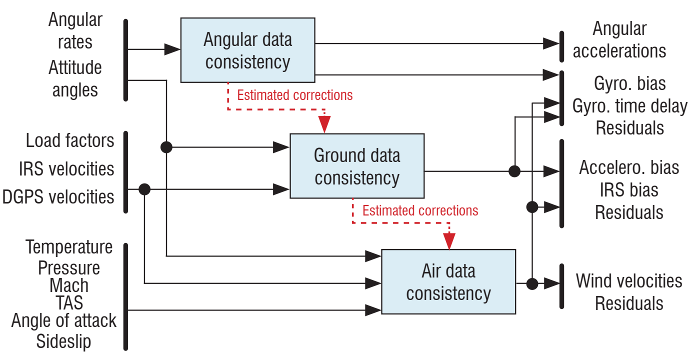


Figure 8 – Block diagram of flight test data checking

In this process, which is outlined in figure 8, the inputs of the three estimators always consist of raw measurements. Only the error parameters are propagated from one step to the next. At the end of the KF, results are processed backward in time by a Rauch smoothing algorithm, to improve the estimation accuracy and to estimate the initial state. Smoothing residuals are also computed to check the proper adjustment of the Kalman error models *a posteriori*. Based on this residual computation, an iterative technique was implemented for an automatic adjustment of the variances of process and measurement noises. This method is aimed at satisfying the agreement between theoretical and experimental variances of the residuals. This tool was also extended to air data reconstruction at low speeds in ground effects. The introduction of variable measurement error variances along the flight path enables some aerodynamic disturbances to be compensated for in AoA measurements during takeoff phases.

Figure 9 shows a typical result of corrections for the AoA. The validity of clinometric air data is limited below 25 m/s, due to losses in sensor sensitivity. Moreover, these measurements are forced to zero below 5 m/s. Wind components are held constant at their latest value estimated during smoothing with the air data nominal accuracy. During the first seconds of climb, the vertical wind component computed from raw AoA measurements shows unlikely variations, which are mitigated by the KF with non-stationary noise covariances. To sum up, consistency checking is an important part of flight test data processing prior to aircraft modeling. It provides an estimate of the sensor errors and of unmeasured or poorly measured variables, and thus can help to save a lot of time during the following modeling tasks.

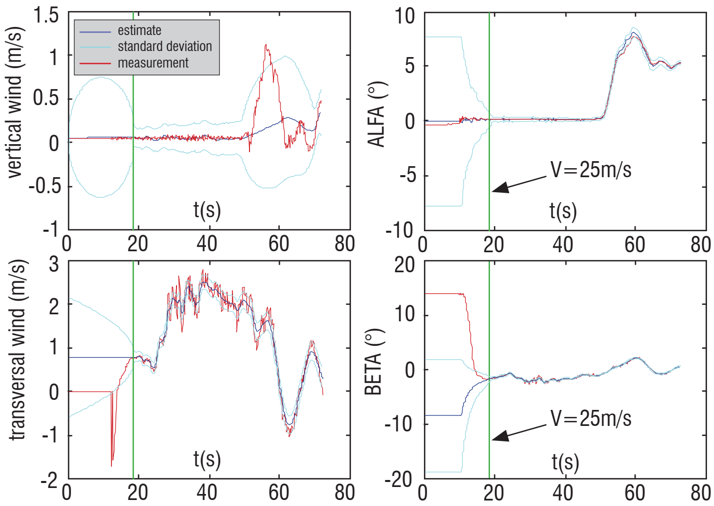


Figure 9 – Air data reconstruction for a take-off test

New estimation techniques: particle and Sigma-point Kalman filters

A necessary step for modeling, identification or fault diagnosis often consists in fully reconstructing the system state. In aeronautical applications, the A/C state is only partially measured and the reconstruction of the full state involves a classical state estimation task. Two kinds of state estimation can be distinguished, depending on whether the application should run on-line or not. In this section devoted to flight tests processing, only off-line applications are considered.

The Extended Kalman filter (EKF), supplemented by a Rauch smoothing algorithm, is the most widely used method taking into account nonlinear models with uncertainties or unknown inputs. It is implemented by linearizing the nonlinear models about the current estimate. Such a numerical technique using finite differences can raise practical problems with strong nonlinearities of the aerodynamic model at high angles of attack. Recent approaches address the model linearization issues of the EKF with approximations of the probability density of the estimated state x_k (at time k). Some of these represent this probability distribution by a minimal set of N_p weighted sample points (given the measurements $z_{1:k} = (z_1, \ldots, z_k)$):

$$p(x_k / z_{1:k}) \approx \sum_{i=1}^{N_p} W_k^{(i)} \delta(x_k - \chi_{k/k}^{(i)})$$
$$\text{with } \sum_{i=1}^{N_p} W_k^{(i)} = 1 \text{ and } W_k^{(i)} \geq 0 \quad (\forall i) \tag{5}$$

where $W_k^{(i)}$ is the weight associated to the sample point $\chi_{k/k}^{(i)}$ and $\delta(.)$ is the delta Dirac density. For instance, the Unscented Kalman Filter (UKF) selects the sample points (also called Sigma Points) by deterministic methods in order to match the mean and covariance of the true probability density [27]. These sigma points are then propagated through the nonlinear function. An augmented formulation of this algorithm is able to propagate state and measurement noises through model nonlinearities. Specific implementations such as square-root or UDU UKF can improve the numerical stability for sigma point computations. Moreover, the use of sigma points can be generalized to solve the smoothing problem [58] and to compute measurement and state residues. In the same vein, the particle filters [1] consist in iteratively updating an approximate description of the filtered distribution $p\left(x_k / z_{1:k}\right)$ (figure 10). This description requires a set of random samples (or particles) with associated weights. As the number of samples becomes very large, this Monte-Carlo characterization is more accurate. Then the key point consists in a recursive propagation of the weights and support points when new measurements are obtained.

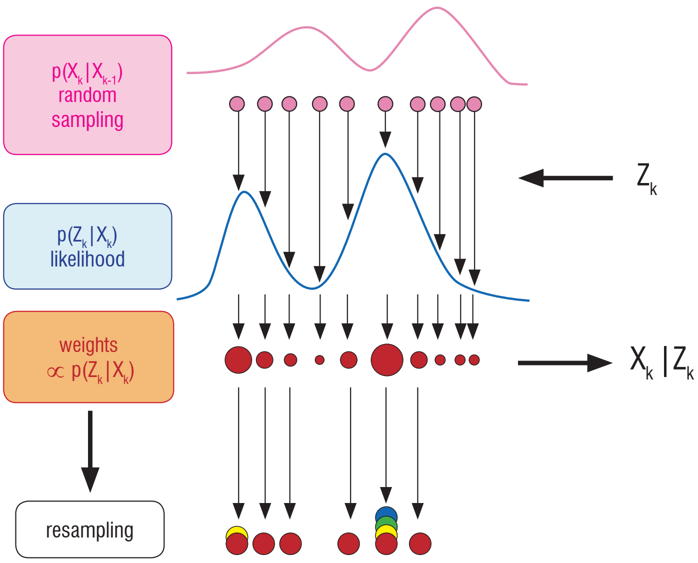


Figure 10 – Principles of particle filtering algorithms

Again, various versions of particle filter algorithms depend on *a priori* choices (like the resampling method, etc.) and attempt to counteract the difficulties encountered with the simplest version. The best example is the *Rao-Blackwell*ized particle filter (also called marginalized particle filter [7]) which exploits the presence of a linear Gaussian substructure in the state equation. Thus, the corresponding linear components of the state can be optimally estimated by a KF. The resulting filter combines a particle filter for the estimation of the nonlinear components with a classical KF for updating the particles in the linear state space. This procedure is worthwhile on two accounts: it reduces the particle number as well as the variance of the estimation error. Other EKF alternatives approximate the filtered density with a weighted sum of Gaussian densities:

$$p(x_k / z_{1:k}) \approx \sum_{i=1}^{N_p} W_k^{(i)} N(\hat{x}_{k/k}^{(i)}, P_{k/k}^{(i)})$$
$$\text{with } \sum_{i=1}^{N_p} W_k^{(i)} = 1 \text{ and } W_k^{(i)} \geq 0 \quad (\forall i)$$

Such methods (called Gaussian Mixture Filters [30]) do not need sampling techniques, as is the case with particle filters. At each iteration, the number of Gaussian densities used for the *a priori* density is multiplied by the number of Gaussian densities used for the noise models. In order to avoid an exponential increase of Gaussian densities, an elimination mechanism of the low weight components is added to the algorithm.

Among the various situations of interest, the estimation of delays was retained to evaluate these new estimation methods. Indeed, the recording systems for in-flight data acquisition rarely perform a synchronous sampling of all measurements. This is the reason why differential delays exist between some measurement subsets. The estimation of these delays involves a strongly nonlinear filtering problem. This is noticeable with the EKF, which suffers from its linearization step, whereas the UKF gives a more accurate estimation of the input delays. This application is a good illustration of the UKF ability to take strong nonlinearities into account. Similarly the *Rao-Blackwell*ized version of the particle filter offers a good compromise between the accuracy of the estimates and the number of required particles.

Another interesting application comes from sensor fault detection. For instance, local measurements of airflow characteristics, performed by anemo-clinometric sensors, often produce errors that are difficult to model. Corrections are applied to provide the modulus and direction of the aerodynamic velocity. Despite these corrections, some undesirable effects (such ground effects, etc.) are not cancelled. Literature reports few approaches dedicated to sensor fault detection and non-stationary noises, which are interesting to test through this specific example. Amongst the various tested approaches, the *Rao-Blackwell*ized particle filter and the stochastic M algorithm (combining the pros of the particle and Mixture Gaussian filters [76]) offer a better performance.

Identification techniques

Identification in the time domain

The equations of motion of a rigid body A/C are derived from the fundamental principles of classical mechanics. The external forces involved in these equations are the propulsion and aerodynamic forces, and gravitational attraction. The uncertainties in this model mostly concern the aerodynamic effects. Consequently, the fitting of the aerodynamic model within the whole flight envelope is the main purpose of the identification process.

Parameter identification methods

Equation Error type approaches

Since EE methods are mostly applied to Linear-in-their-Parameters (LP) models (*i.e.* linear with respect to the parameters to be identified), only this type of model is considered in this section. An extension to the nonlinear case will be considered afterwards. Therefore, the model obeys:

$$Z = \Phi\,\theta + \varepsilon \tag{6}$$

where Z is a $(N\times 1)$ vector gathering all measurements, Φ is the $(N\times n_\theta)$ regression matrix, and θ is the $(n_\theta\times 1)$ vector of parameters to be identified. Therefore, ε is the $(N\times 1)$ vector of errors and N is the total number of available samples. The columns of Φ are called the regressors and are assumed to be linearly independent (*i.e.* $\mathrm{rank}(\Phi)=\dim(\theta)=n_\theta$). In addition, the model structure is supposed to be fixed and known *a priori*, because it results from Lagrangian equations, Newton's law, Ohm's law or Maxwell equations.

In aeronautics, this method is commonly used to estimate the linear coefficients involved in the analytical expression of aerodynamic developments and, more generally, as a preliminary step in the identification process. As an example, let us consider the following linearized lift modeling, $Cz = Cz_0 + Cz_\alpha\,\alpha + Cz_q\overline{q} + Cz_{\delta_e}\delta_e$, where $Cz_0, Cz_\alpha, Cz_q, Cz_{\delta_e}$ are the stability and control derivatives to be estimated, α is the AoA, $\overline{q}$ is the adimensional pitch rate and δ_e the elevator angle. This model is LP since we can write (at sample k):

$$Z_k = Cz(k)\,,\quad \Phi_k = [1 \quad \alpha(k) \quad \overline{q}(k) \quad \delta_e(k)] \tag{7}$$
and $\theta = [Cz_0 \quad Cz_\alpha \quad Cz_q \quad Cz_{\delta_e}]^T$

Since values like Cz are not directly sensed, this approach at first requires these global aerodynamic coefficients, which constitute the pseudo-measurements of the model to be identified, to be reconstructed. Hence, they are computed from the linear and angular accelerations, which are measured or derived from the flight test instrumentation. Keeping the z-axis example, this is achieved by inverting the flight mechanics equation $mg\,n_z = -(F_z^{aero} + T_z^{eng})$, where n_z is the normal load factor computed from the accelerometers, T_z^{eng} is the normal component of the engine thrust and F_z^{aero} is the normal aerodynamic force permitting the previous Cz to be computed *in fine*. Practically, the measured input variables used in this process are corrupted by noises and calibration errors, especially in the case of air data. To reduce the impact of these errors, which can result for example in a correlation between Φ and ε, a KF technique is relevant to estimate A/C state variables and aerodynamic coefficients jointly (see figure 18).

Usually, the vector θ is identified with the well-known Ordinary Least Squares (OLS) technique, which minimizes the following criterion: $J(\theta)=\|\varepsilon\|_2^2$. The OLS solution is then given by:

$$\hat{\theta}_{LS} = (\Phi^T\Phi)^{-1}\Phi^T Z \tag{8}$$

In most cases, OLS is not statistically efficient, and the Weighted Least Squares (WLS) technique is often preferred to OLS. For this purpose, a $(N\times N)$ weighting matrix Ω is introduced and the WLS solution is then given by:

$$\hat{\theta}_{WLS} = (\Phi^T\Omega\,\Phi)^{-1}\Phi^T\Omega\, Z \tag{9}$$

LS techniques are easy to use and were successfully validated through several application fields such as robots, motors, cars, compactors and aircraft (see for example [12,28,36,73]). However, LS techniques provide consistent results if and only if the observation matrix Φ is statistically not correlated with the error vector ε (*i.e.* $E(\Phi^T\varepsilon)=0$). This is the reason why LS techniques are often coupled with an appropriate data filtering to make the regression matrix Φ practically deterministic. However, as pointed out in many papers, it cannot be proven that LS estimation is consistent without additional information [6,11,63]. Consequently, techniques dealing with a noisy observation matrix have been studied. One among others is the Instrumental Variable (IV) method. The idea consists in introducing an instrumental matrix $(N\times n_\theta)$ denoted as V and pre-multiplying the two members of (6) by V^T; with the strong assumptions that $E(V^T\varepsilon)=0$ and $V^T\Phi$ is invertible, the IV estimation is thus given by:

$$\hat{\theta}_{IV} = (V^T\Phi)^{-1}V^T Z \tag{10}$$

The major problem is of course to find valid instruments. The best choice consists in building the instrumental matrix from simulated data. This choice is particularly suitable for physical systems [77]. Though the IV technique has been studied in many papers, there are only a few real world applications. Nevertheless, this technique has been recently extended to robots with excellent results [23].

Output Error and Filter Error type approaches

The output error (OE) method is probably the most widely applied method to parameter estimation for aircraft models. The principle is again very simple: A/C model parameters (aerodynamic derivatives, state and output biases, initial conditions) are fitted in order to minimize the following cost function:

$$J(\theta) = \frac{1}{2}\sum_{k=1}^{N}[z_k - y_k]^T R^{-1}[z_k - y_k] \qquad \left\{+N\log[\det(R)]/2\right\} \tag{11}$$

where y represents the vector of n_y model outputs, z the $(n_y\times 1)$ measurement vector, N is the number of samples and R is the covariance matrix of the measurement noises. Solving this optimization problem according to the ML principle also allows R to be estimated with a relaxation strategy [29]. In practice, the diagonal elements of R are often adjusted by the user, to balance the output contributions according to the measurement accuracy (and the last term of (11) is dropped). It is worth noting that the principle of the OE method assumes that the control deflections used to simulate the A/C model behavior are noise free. In addition, for more than 30 years, it has been proven that the variance of the parameter estimates can be computed at the same time, an approximation being provided by the Cramer-Rao lower bounds (see *e.g.* [41]). However, an imperfect knowledge of the aerodynamic model structure can result in a degradation of the parameter accuracy, resulting in a spread of the aerodynamic derivatives dependent on the flight conditions. In this case, the uncertainties evaluated via the Cramer-Rao bounds do not account for these errors. Moreover, the processing of flight tests performed in the presence of turbulence can also lead to an increase in the parameter scattering.

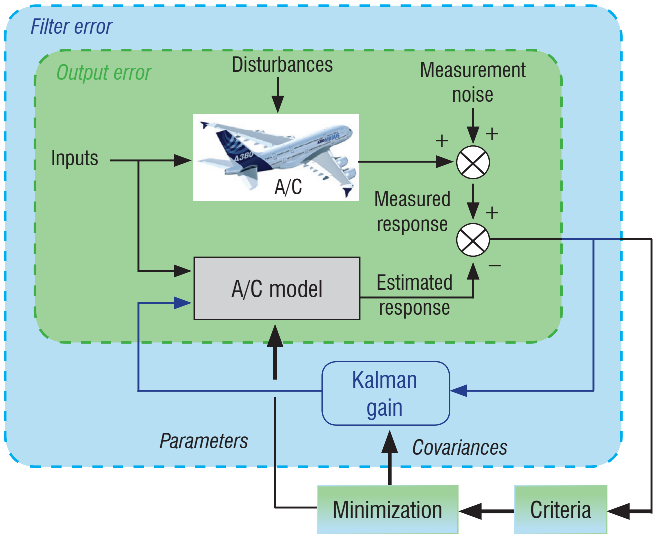


Figure 11 – Block diagram of OE/FE methods

Owing to these problems, the ML principle allows the OE approach [41] to be generalized. The previous two types of disturbances are then represented by process noises, which can be accounted for in a more general formulation called the filter error method (FE). This technique can be considered as an extension of the OE method and incorporates a state estimator, KF type (figure 11). Applied to parameter identification, the estimation, according to the ML principle, gives the parameter value that maximizes the probability of the measured data for a given set of parameters. The likelihood function is defined from the probability distribution $p(Y/\theta)$ of the response $Y=(y_1,\ldots,y_N)$ as $L(\theta)=p(Y/\theta)_{Y=Z}$. Assuming a linear state space representation with Gaussian white noises for measurement and process equations, the ML estimate can be derived by minimizing the following cost:

$$J(\theta)=\frac{1}{2}\sum_{k=1}^{N}[z_k-y_k]^T S^{-1}[z_k-y_k]+N\log[\det(S)]/2 \qquad (12)$$

where y corresponds, from now on, to the predicted observations resulting from the KF and S is the innovation covariance of the KF. In the most general formulation, this method can be used to estimate all the parameters, *i.e.*, the model parameters, the initial states and the covariance of process and measurement noises (Q and R). Several formulations have been proposed for linear models, to solve the numerical and the convergence issues [42]:

- Natural formulation: the unknown variances (in Q and R) are estimated, as well as the model parameters;
- Innovation formulation: the elements of the Kalman gain matrix are directly estimated, instead of noise variances, and the innovation covariance is experimentally estimated from the filtering residuals;
- Combined formulation: this algorithm takes the principle of natural formulation and replaces the computed innovation covariance by its estimate from measurements [42]. The computation of the Kalman gain is derived from a modified Riccati equation, which must be solved with an additional constraint to ensure the filter stability.

Extensions to nonlinear systems have also been derived, but implementations are often restricted to steady state filters, to limit the computational burden [24]. In practice, with nonlinear systems and measurements corrupted with non-white Gaussian noises, an estimation of both process and measurement variances is generally not achievable. However, the simultaneous estimation of aerodynamic model parameters and of (a limited number of) process noise variances can be considered thanks to the direct minimization of the likelihood function. The algorithm adjustment parameters are then limited to the elements of R, as is usually the case with the OE method.

Following this principle, an FE approach has been developed to identify a nonlinear aircraft model. It includes a nonlinear Kalman estimator, operated with a constant gain resulting from the resolution of an algebraic Riccati equation and requires a (numerically) linearized A/C model. The state estimator is implemented in a Gauss-Newton algorithm, a common optimization method for OE approaches. This 2nd order method is based on a local quadratic approximation of the Hessian matrix and only requires a computation of the output sensitivity derivative vector. An additional mechanism was implemented to decrease the step size of parameter changes automatically, if the criterion increases. The gradient computation has been extended to allow the optimization of the process noise covariance, which results in a non-quadratic formulation [13]. The corresponding estimated parameters are defined by the logarithms of the noise standard deviations. This change of variable cancels the sign constraints, and improves the convergence rate.

The simultaneous processing of multiple flight tests leads to defining a subset of parameters (*i.e.* aerodynamic coefficients) that are shared by all tests and to cope with specific parameters, such as state and output biases, plus initial conditions, which must be adjusted for each experiment. Process noise variances can be globally defined for all the experiments, or separately processed. Output sensitivity derivatives are numerically estimated restricting the simulations to those required by the previous test-dependent parameters. Apart from accounting for process and measurement noises, this method offers several advantages compared to the OE approach: a faster convergence rate, fewer local minima, an improved convergence robustness to initial model errors and the possibility of identifying unstable models [25]. Regarding the latter, the gradual evolution towards new unstable A/C configurations can lead to difficulties in the use of the standard OE approach. Indeed, this technique involves an open-loop integration of the model, which may cause numerical divergence during the simulations. The state estimator implemented in the FE method has intrinsic stabilizing properties and is thus well suited for the identification of unstable models. Without process noise, the steady-state Kalman gain matrix is not null as it is with OE, but is rather a constant gain that shifts the unstable poles in the left half-plane.

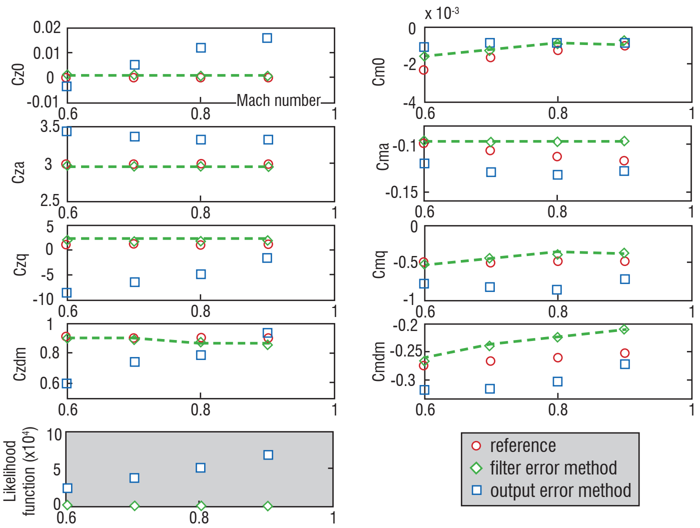


Figure 12 – Estimates of aerodynamic derivatives (FE vs. OE)

To illustrate this, some simulation results are presented in figure 12, to show the benefits of applying an FE approach to the identification of aerodynamic derivatives with a mismatched model. A linear aerodynamic model is estimated, whereas the reference simulation was performed with nonlinearities in the control derivatives. Each plot displays the variation of the aerodynamic derivatives with the Mach number. Coefficients estimated with the FE method match well with reference values, whereas several parameters delivered by the OE method exhibit a drift.

Structure of the aerodynamic model

The aerodynamic coefficients are usually expressed as look-up tables or strongly nonlinear functions, depending on multiple parameters (configuration, Mach, AoA, sideslip, deflection angles). However, the parameter estimation can be tackled either in a linear or weakly nonlinear framework, by using only tests flown at close flight conditions, or in a strongly nonlinear framework by fitting the model directly into a large part of the flight envelope. The 6dof flight mechanics model is usually split into two largely independent sets of equations describing the longitudinal and the lateral-directional A/C motions. This way, the identification problem is reduced to two smaller problems, which are easier to solve. The main difficulties result from the strong nonlinearities in the Mach number and AoA as far as the longitudinal axis is concerned, and from the roll-yaw coupling in the lateral case. EE-OE-FE minimizations can be used, depending on the context. Whatever the method, it is crucial for the aerodynamic corrections to remain physically acceptable.

Weak nonlinearities

Usually, the identification process for the lateral-directional coefficients can be conducted by using flight tests flown with about the same configuration, Mach number, AoA and at low sideslip angles. The nonlinearities, which mainly depend on sideslip, do not act and the aerodynamic nonlinear effects come only from control surface efficiency. Either additive or multiplicative corrections can be estimated by minimizing the weighted errors between simulated outputs and A/C measurements. In addition, a smoothing constraint is generally applied to the efficiencies, in order to limit their fluctuations and to ensure the consistency of the corrections. Accordingly, a software package was developed by DCSD for identifying the lateral model of an aircraft and was used by Airbus for several programs from the A340 up to the A380 [37].

The aerodynamic model identification is based on aircraft-wide measurements and delivers global corrections for the aerodynamic coefficients. If the aerodynamic model is split into an aircraft with and without tailplane, as is the case with Airbus modeling, the question is raised regarding the distribution of the corrections among the various parts. A conceivable solution to this problem would consist in processing measurements that are sensitive to local effects, such as load measurements, besides standard flight parameters. The drawback is that this kind of measurements can be corrupted by a high level of noise. This idea was implemented to estimate the lateral-directional coefficients of an A340-600, in high-lift configuration, the additive measurements being restricted to fin loads sensed by strain gages. Among the split coefficients corresponding to an aircraft with and without vertical stabilizer (fin), only sideslip effects could be accurately identified.

Neural and hybrid approaches

Techniques based on linear or weakly nonlinear models are efficiently used as a first step of the identification process. However, when a global model is sought, *i.e.*, a model that is valid throughout the flight domain and that includes all aircraft specific nonlinearities, appropriate approaches and techniques must be applied. The task is all the more complex because the nonlinearities are only available in the form of multivariate look-up tables, which are not very convenient for identification purposes. In industry, this global modeling is typically obtained after a long iterative process mainly based on EE algorithms, the result of which is highly dependent on the skill of the performing engineers. For that matter, DCSD has been developing a so-called *hybrid identification* approach for several years, which is aimed at proposing a more automatic processing of flight data. The ideal thing would be to tune all of the model parameters in a single step (linear and nonlinear ones) using all of the available test data; thus, the tools have been designed for that purpose. In practice, a sequential approach often remains useful.

Hybrid identification refers to the hybridization between classical linear approaches (in the TD) and specific methods intended to handle the model nonlinearities. The various methods classically used can be implemented (EE, OE or FE algorithms) and this has been achieved through extensive algorithmic adaptations. As for the representation of the nonlinearities, the choice was made in favor of Neural Networks [21]. NN are commonly used as *surrogate models* to replace the system or the reference model when it is too complex or time consuming for achieving some tasks like optimization, parameter identification, etc. [62]. They are particularly well suited for modeling complex and unstructured nonlinear systems, whether static or dynamic [15,16]. In the hybrid approach, NN are typically used to replace the look-up tables describing the various nonlinearities of the aerodynamic model [39]. This allows an algorithmically efficient identification which, additionally, does not require *a priori* knowledge (*e.g.* the look-up index). This kind of implementation of NN is thus grey-box type and it preserves the physical meaning and structure of the aerodynamic developments. Let us provide an example of how NN are introduced in the model. The equation below shows a somewhat simplified description of an A/C pitching moment coefficient Cm, as it appears in longitudinal flight dynamic equations [3]:

$$Cm = S\,l\,Pd\ [\underbrace{Cm_0}_{f(M)} + (x_{cg} - \underbrace{x_F}_{f(M)})\ \underbrace{Cz_\alpha}_{f(M)}\ \alpha + \underbrace{\eta_{NL}}_{f(Pd,M)}\ \underbrace{\Delta Cm_{NL}}_{f(\alpha,M)} + \dots\ ] \qquad (13)$$

where α, M, S, l, Pd are AoA, Mach number, reference area and length, and dynamic pressure respectively, whereas x_{cg} and x_F correspond to the longitudinal abscissae of mass and aerodynamic centers. Cm_0, x_F, Cz_α, ΔCm_{NL} and η_{NL} represent aerodynamic and aeroelastic coefficients, which contribute to the global Cm and which can be replaced by neural modules to automate and improve the identification process.

Two options are available: either this time dependent coefficient is directly compared with its counterpart extracted from flight data throughout the sequence of tests available (EE), or it is integrated into the flight dynamic equations to allow a minimization between measured and simulated state variables (OE). Both methods benefit from of the analytical and differentiable formulations of NN, which make it possible to perform quasi-exact parameter optimization (unlike purely numerical approaches using finite differences). Much CPU time is also saved for the derivative estimates required by the sensitivity equations, which is quite valuable, especially for OE or FE approaches. The software developed by DCSD mainly relies on the use of local models, such as Radial Basis Function Networks (RBFN). As opposed to global models, such as Multi-Layered Perceptrons (MLP), local models keep the aerodynamic model readable and make it easier to perform identification from partial data relative only to portions of the flight domain [49]. The output $\hat{y}_k$ predicted by a RBFN, *e.g.* $\hat{C}z_\alpha$ in (13), complies with the form:

$$\hat{y}_k = f(e_k) = \sum_{j=1}^{m} w_j\, \phi_j(e_k) \qquad (14)$$

with $\phi_j(e_k) = \exp[-\sum_{i=1}^{n} (e_k^i - c_{ji})^2 / \sigma_{ji}^2]$

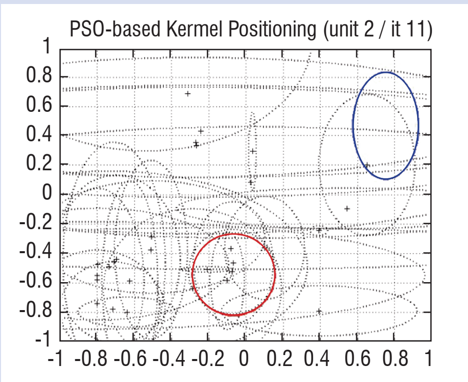
denoting e_k^i $(\forall i \in [1,n])$ the value of the i^{th} explanatory variable for the k^{th} data sample (*i.e.* α, Pd or M in (13)), and assuming that $\hat{y}_k$ is scalar, to simplify the writing. In the expression (14), the functions ϕ_j are the nonlinear regressors, which allow internal parameters c_j (centers) and σ_j (radii) to appear by choosing Gaussian radial functions, a rather common choice (see figure 13 without dotted connections). w_j are the regression parameters also to be determined during the optimization process and m defines the number of regressors (*a priori* unknown).

Box 1 - Local Linear Modeling via Neural Networks

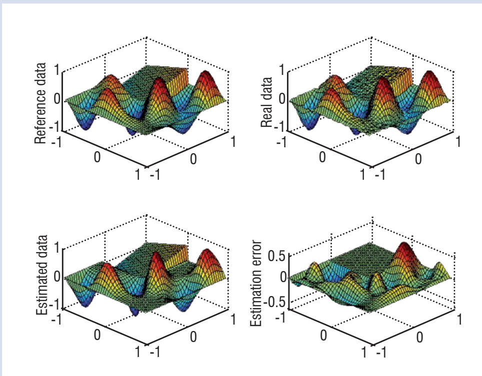
A nonlinear model can be either linear, nonlinear or both in regard to its internal parameters. Within the framework of NNs, the latter case corresponds for example to the MLP [15], but also to the RBFN when the centers and radii of the radial units are optimized [16]. Clearly, this is the most general formulation since LP models are nothing but a special case and it is also the cause of NN theoretical properties as parsimonious approximators. However, the joint optimization of the whole set of model parameters (linear and nonlinear) practically results in ill-posed problems, which are likely to converge very slowly to solutions conveying the trade-off between performances and regularization. This is why LP models are always quite common practice, since more simple and robust algorithms can be adopted, driven from the classical methods in use for adapting linear regression parameters. Hence, by taking advantage of their features, we can proceed to structural identification, *i.e.*, to determine the best set of regressors from the available data.

To choose the regressors ϕ_j, we will focus on methods based on forward selection, as opposed to other methods which consist in selecting a full set of candidate regressors at first, before removing the less relevant ones one by one (backward elimination). Forward selection starts with an empty subset and the regressors are added one at a time in order to gradually improve the results. Therefore, the final number of regressors is not known in advance and the computational cost is reduced since the regression size will become large only if it is required to reduce the modeling error. Forward selection is computationally efficient, but constructive algorithms can be sped up even further thanks to a preliminary orthogonalization process, making use of the famous Gram-Schmidt technique [19,20]. Moreover, this procedure allows the successive regressors to be decoupled from each other, and hence allows their individual contribution to be evaluated regardless of those already recruited for the modeling.

To implement this forward selection, two options are available: ❶ to first define an initial pool of candidate regressors from which the most relevant ones will be selected, ❷ to determine each regressor individually as the process goes on, which generally amounts to optimizing the kernel functions in the input space. Within class ❶ is the entire range of classical and direct methods that locate the regressor kernels quite arbitrarily: in a subset of the data samples, on the knots of a lattice derived from a gridding of the input space, by using data clustering or self-organization techniques. Class ❷ has to do with optimization techniques, but to avoid the problems inherent to classical methods (convergence, sensitivity to initial values) global optimization is favored, among which evolutionary algorithms have done particularly well for some years. Recently, a new metaheuristic also arising from biological inspiration (bird flocking or fish schooling) was imagined, known as Particle Swarm Optimization (PSO). The collective behavior of the particles looks like a swarm of living beings (*e.g.* bees): an individual discovering a good spot passes on the information to the others, which use it to direct their next moves. Therefore, the swarm represents a set of autonomous and interacting agents cooperating to solve a problem. The members of a group benefit from the accidental discoveries, as well as the experience acquired by other individuals. Similarly to the evolutionary case, the method is based on an iterative and stochastic process [20].



Video 4 - PSO-based kernel positioning
Video - http://www.aerospacelab-journal.org/al4/relevant-issues-for-aircraft-model-identification



Video 5 - Modeling through LLM
Video -http://www.aerospacelab-journal.org/al4/relevant-issues-for-aircraft-model-identification

The coupling of this PSO algorithm with the constructive approach based on forward selection allows structural and parametric optimizations to be proceeded to jointly, for various types of regressors with local basis. The interested reader will find more details in [20,21]. In the KOALA tool (*Kernel Optimization Algorithm for Local Approximation*) developed by DCSD, this approach is applied to various kernel-based NNs, such as RBFN and LLM. To illustrate the working of this tool, videos 4 and 5 display the gradual improvement of an LLM during the iterative process involving the forward selection and optimization of kernels. The coefficient chosen corresponds to a complex L-shaped membrane including a constrained area (hyperplane in $[-1,0]\times[0,1]$) to prove the capability of the method to take this type of constraints into account. Video 4 illustrates some PSO issues: the black crosses and dotted circles represent the swarm particles during the internal PSO cycles (centers and radii parameters), whereas the red circles represent the current best individual and the blue circles represent the kernels already selected. Video 5 displays the reference coefficient (top left) to be modeled from noisy observations (top right), the current LLM model (bottom left) and the current modeling error (bottom right), as the forward process unfolds (until 16 RBF units are created to fulfill a trade-off between accuracy and complexity). It is also worth noting that this technique is useful for identification purposes (especially EE approaches), as well as for on-board implementation of models with low memory requirements [20] or for synthetizing control laws from sparse approximated expressions [19].

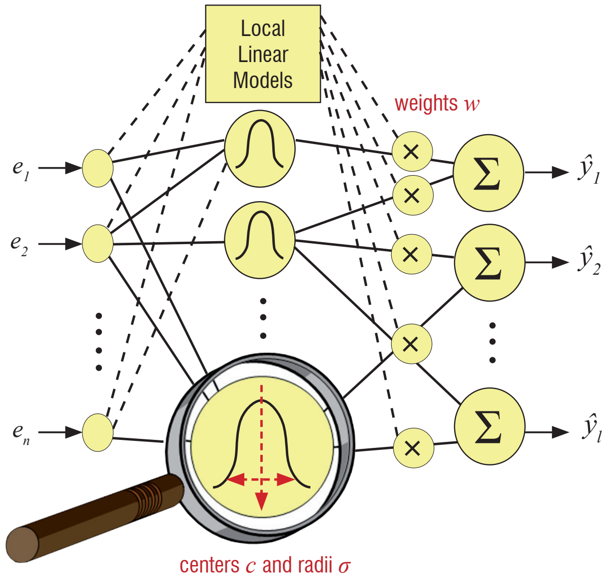


Figure 13 – Architecture of RBFN and LLM

Besides RBF nets, other types of local models can be usefully implemented (see box 1). This is the case with LLM (*Local Linear Models*), which generalize RBFN by replacing the linear weights by an affine expression depending on the model inputs, but are also related to other local models like some Fuzzy Inference Systems. By defining an extended set of regressors $\phi_l^{\#}$, the generic form (14) used to represent LP models thus becomes:

$$\hat{y}_k = f(e_k) = \sum_{j=1}^{m} \left(\sum_{i=0}^{n} w_{ji} e_k^i\right) \phi_j(e_k) = \sum_{l=1}^{m(n+1)} w_l\, \phi_l^{\#}(e_k) \qquad (15)$$

with $e_k^0 = 1$ to include the constant terms of the local affine modeling into the 2nd sum. It is thus expected that fewer RBFs will be required to achieve the same accuracy in most applications (see the dotted connections in figure 13).

Practically, the purpose of an automated identification in large areas of the flight domain has raised a new need: specifying constraints to be followed by the nonlinearities (*i.e.* the NN outputs). Constraints are a way to compensate for insufficient or sparse test data and to introduce some kind of expertise into the problem. For instance, the freezing of output levels may be required in some zones (*e.g.* ΔCm_{NL} in (13) should remain null at low AoA and low Mach, so that it does not interfere with other terms); it may also be desired to smooth the nonlinearity, or to connect identified and pre-flight models in areas where no flight data is available. Constraints are thus enforced by mechanisms relying for example on criteria penalty. Various forms of penalties are used, depending on the goals: constrained values, smoothing, regularization, etc. This in turn raises the question of choosing and tuning these hyperparameters, which should also be as automated as possible: this topic is currently being addressed.

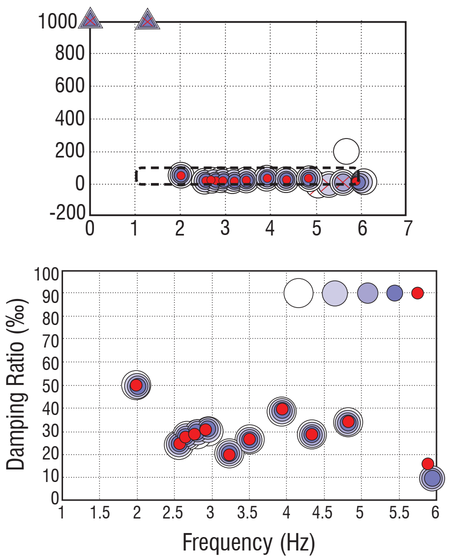
Identification in the frequency domain

Flexible A/C and flutter analysis

Among the various phenomena that can affect the flight of an A/C, flutter is one of the most feared events, since this dynamic instability can lead to a sudden destruction of the airplane (see box 2). One of the major goals of the series of flight tests undertaken for any new aircraft is to check that the airplane is free of any flutter tendency in the whole set of flight conditions. Current flight tests are performed under stabilized flight conditions (at constant speed and at given Mach number). Under each condition, excitation signals (frequency sweeps, pulses) are successively applied to the structure through the control surfaces. The measurements of the A/C response are transmitted by telemetry to the ground test center in real time, where they are used to estimate the modes. The damping ratio estimates obtained under each stabilized condition, allow a trend to be drawn up, as a function of airspeed, which is useful to evaluate the stability of the next higher airspeed condition and to clear the airplane to this condition.

Onera has been working for many years in close collaboration with Airbus for flutter flight surveillance and has developed a large expertise in this topic [22,57,64-71]. DCSD not only develops identification tools that are currently used in the Toulouse ground test center of Airbus [57,64], but it also tackles most of the aspects of the identification process. Optimized excitation procedures are investigated and proposed for industrial use [22,70,71]. Evaluation tools based on high dimensional aeroelastic models were also developed [67,68]. Concerning the identification tools, prototypes are implemented involving all the aspects: raw data pre-processing, identification algorithms, supervision in order to determine the best model order and ergonomic graphical interfaces (see figure 14).

Owing to the operational context of the flutter tests, involving real-time monitoring, identification algorithms should comply with stringent requirements. Let us mention here the major constraints. First of all, the flight test conditions are not really favorable to an accurate identification. On the one hand, since the A/C operates under operational conditions, the measurements are affected by the ambient noise due to the airflow around the aircraft. Sometimes, the data is also corrupted by air turbulence when the aircraft encounters wind gusts. On the other hand, the excitation signals applied to the control surfaces are constrained in amplitude, frequency and shape. Consequently, many structural modes are not excited efficiently enough.



	30	28	26	24	22
MODES	1.98 50	0.00 1000	0.00 1000	~~0.00 1000~~	1.98 51
	2.57 24	1.27 1000	1.27 1000	~~1.27 1000~~	2.57 25
	2.69 28	2.00 50	2.00 50	2.00 50	2.69 28
	2.81 29	2.57 25	2.57 25	2.57 25	2.81 28
	2.93 30	2.69 29	2.69 29	2.69 29	2.93 30
	3.23 20	2.81 30	2.81 30	2.81 30	3.24 20
	3.51 27	2.94 30	2.94 30	2.94 30	3.50 26
	3.94 39	3.23 20	3.23 20	3.23 20	3.94 40
	4.33 29	3.51 26	3.51 26	3.51 26	4.34 28
	4.82 34	3.94 39	3.94 39	3.94 39	4.83 34
	~~5.03 -11~~	4.34 28	4.34 28	4.34 28	
	5.28 -2	4.82 33	4.82 33	4.82 33	
	5.56 -1	~~5.27 -1~~	~~5.56 -1~~		
	5.67 199	5.95 10			
	6.07 16	5.56 -1	5.95 10	5.95 10	5.89 16

Figure 14 – Example of a graphical interface used for order determination

The second demanding requirement is that the algorithms must operate in a fully automated and near real-time way, since the crew is awaiting clearance before going on to the next test condition. It is

Box 2 - The flutter phenomenon

In aeronautics, aeroelasticity is the science that studies the interaction between the inertial, structural, and aerodynamic forces acting on an aircraft. It was introduced by Collar as early as 1947. Aeroelasticity deals with several phenomena that may occur during flight. Among these, flutter is the most hazardous one. It is a dynamic instability whereby the oscillations of the structure extract energy directly from the airstream. Flutter can build up very quickly and cause the destruction of the aircraft. Any physical object is subject to its natural modes of vibration. When placed in a strong airflow, the aerodynamic forces alter the characteristics of these natural modes and flutter will happen if a positive feedback occurs between the natural vibration and these forces. If the energy extracted from the airflow is greater than the natural damping of the system, the level of vibration increases and leads to instability. Flutter can occur in any structure exposed to aerodynamic forces. One famous example is the collapse of the Tacoma Narrows Bridge (USA) in 1940 (see video 6 for several illustrations including this one).

Video 6 - The flutter phenomenon
Video - http://www.aerospacelab-journal.org/al4/relevant-issues-for-aircraft-model-identification

A schematic representation of the flutter phenomenon is also given by figure B2-1, which depicts a typical flutter case for airplanes. It results from the coupling between the bending and torsional modes of a wing. If these modes have similar frequencies and produce in phase oscillations under some flight condition, then the torsion of the wing induces variations in the lift due to the variations of the AoA. When these oscillations in the lift are in phase with the bending mode, they amplify the amplitude of the oscillations for this mode and hence flutter occurs. The physical modeling of the aeroelastic behavior is quite complex: it is based on the modeling of structural dynamics and unsteady aerodynamic effects. For complex systems such as an aircraft, the exact modeling of all structural aspects under all flight conditions is not possible. Therefore, a thorough flight testing is the only way to guarantee that an aircraft is free of flutter.

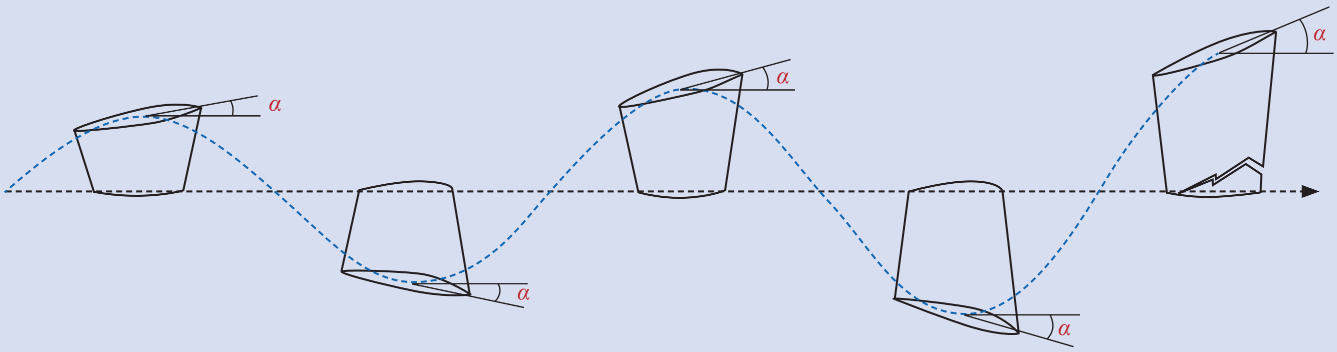


Figure B2-1 – Illustration of the flutter phenomenon

noteworthy that about one thousand identification runs are required for the certification of a new aircraft. This also claims for a high processing efficiency. Fully automated procedure is of capital importance, in order to relieve the ground operator who is put in charge of monitoring flight safety. To achieve this task, the algorithms must cope with high dimensional systems. Considering the number of modes that can be reasonably estimated and the number of available measurements, it turns out to be necessary to identify systems including 1000 to 5000 parameters. Hence, the algorithms must be very reliable and very robust to numerical errors.

The FD is particularly appropriate to the test conditions since we can focus only on the frequency band of interest. The amount of data to be processed is also greatly reduced, resulting in improved computation times. Hence, the tools developed for flutter flight test surveillance are based on a parametric approach in the FD [64]. A polynomial transfer function has been chosen for the system, since it is very convenient for modal modeling:

$$H(s,\theta) = \frac{N(s,\theta)}{d(s,\theta)} \tag{16}$$

where the denominator $d(s,\theta)$ is a polynomial of degree n_d and the numerator $N(s,\theta)$ is a $(n_y \times 1)$ vector of polynomials of degree n_d, assuming that n_y outputs are processed; $s = j\omega$ is the Laplace transform variable and θ is the parameter vector of dimension $n_\theta = (n_y+1)\times(n_d+1)$, which includes all of the numerator/denominator coefficients to be estimated. This black-box type of modeling is also convenient, since the frequency responses (*i.e.* the values taken by the transfer function for a discrete set of frequencies) may be directly computed from the measured time data by applying non-parametric spectral estimation methods.

The purpose of the identification task is to determine the best model (16), in order to match the estimated transfer $H(s,\theta)$ with these *measured* frequency responses $H_m(j\omega)$ derived from the raw data. The parameter estimation problem is then formulated as a nonlinear optimization problem:

$$\hat{\theta} = \operatorname*{Arg\,Min}_{\theta}\,[J(\theta)]$$
$$\text{where } J(\theta) = \sum_{\omega\in\Omega} \|\mathrm{H_m}(j\omega) - H(j\omega,\theta)\|^2_{\mathrm{W}_\omega} \quad (17)$$

where Ω is the set of frequencies ω located within the band of interest and W_ω is a weighting matrix introduced to take the (varying) quality of measurements into account. A method of iteratively reweighted least-squares is then used to solve this optimization problem. To improve the algorithm implementation, $N(s,\theta)$ and $d(s,\theta)$ are expressed in specific polynomial bases to overcome the conditioning problems encountered with high order polynomials when using conventional bases involving high powers of ω [64].

In the current test protocol, a single excitation signal is used for each test. In the future, in order to shorten the tests duration and hence to reduce the costs, it is contemplated to apply several excitation signals through several control surfaces simultaneously. Then, current developments focus also on MIMO (Multi-Input/Multi-Output) identification methods that are able to satisfy these more stringent operational requirements.

Rigid A/C and on-board monitoring

As seen before, the methods involving the OE minimization are common practice in aeronautics. The criterion is generally expressed in the TD (see eq. (11)), but it can also be formulated in the FD thanks to Parseval's theorem, conveying the principle of energy preservation between the two domains. Hence, it becomes:

$$J(\theta) = \frac{1}{2}\frac{\Delta f}{\Delta t}\sum_{k=1}^{N_\omega}\left[Z(\omega_k) - Y(\omega_k,\theta)\right]^{\dagger} R^{-1}\left[Z(\omega_k) - Y(\omega_k,\theta)\right] \quad (18)$$

where $\dagger$ represents the complex conjugate transpose operator and where the summation is now taken over the N_ω frequencies ω_k of interest, available from the TD to FD transformation ($N_\omega \le N$). The simulated and measured outputs Y, Z are defined in figure 15, whereas Δf and Δt represent the sampling periods in FD and TD respectively.

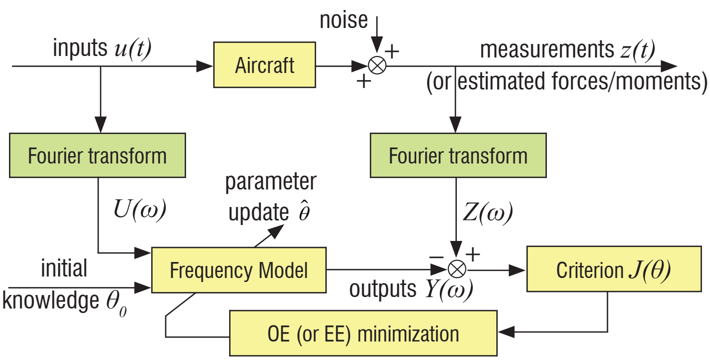


Figure 15 – Principles of identification in the frequency domain

As illustrated by figure 15, the transition to the FD is classically carried out by means of the standard FT of the TD signals. Since they are only available over a limited period of time $[0,T]$, the finite FT is used instead. Practically, two efficient tools are available for computing this quantity, namely the Fast Fourier Transform (FFT) and the Chirp z-transform. The latter permits a desired frequency resolution to be chosen independently from the interval length T, but it is less effective as far as computation time is considered. From N data samples equally spaced over the time interval $[0,T]$, the FFT algorithm calculates N values of the discrete FT over the frequency interval $[0, 2\pi/\Delta t]$, also equally spaced with a step $\Delta\omega = 2\pi/T$. It is also worth noting that a recursive version of the algorithms allows the method to be implemented in real-time applications very efficiently. Apart from these computationally efficient tools making it possible to go from TD to FD, the FD identification approaches have other pros: they do not require an integration of the flight mechanics differential equations to perform a simulation and they enable working within a limited band of frequencies by selecting any range $[0 \le \omega_1, \omega_2 \le 1/2\Delta t]$.

More precisely, let us consider equation (19) which expresses the transformation of the system dynamics into state-space form from TD to FD and let the state and output biases b_x and b_y appear. If we consider frequencies ω_k only multiples of the sampling frequency $\Delta\omega$, which is the case when using the FFT, the right bracket of (19) represent the simplified form of the FD state-space equations. $\delta(\omega_k)$ denotes the Dirac function in the FD, such that $\delta(\omega_k) = 1$ for $\omega_k = 0$ and $\delta(\omega_k) = 0$ else for $\omega_k \neq 0$. $\Delta x = x(0) - x(T)$ corresponds to the discrepancy between the initial and final states.

$$\begin{cases} \dot{x}(t) = A(\theta)x(t) + B(\theta)u(t) + b_x \\ y(t) = C(\theta)x(t) + D(\theta)u(t) + b_y \end{cases}$$
$$\downarrow$$
$$\begin{cases} j\omega_k X(\omega_k) = A(\theta)X(\omega_k) + B(\theta)U(\omega_k) + b_x T\delta(\omega_k) + \Delta x \\ Y(\omega_k) = C(\theta)X(\omega_k) + D(\theta)U(\omega_k) + b_y T\delta(\omega_k) \end{cases} \quad (19)$$

Localized effects in the TD are thus translated into broadband effects in the FD and vice versa. Thus, the initial and final conditions are translated into a bias that affects all frequencies. On the contrary, the biases that act as broadband inputs in the TD modify only the zero frequency. To get the most out of these specificities, it is generally worthwhile to also discard this zero frequency during the identification stage, which avoids state and output biases having to be estimated. Thus, (19) is further simplified and only the Δx components need to be estimated in addition to other parameters θ, if not zero.

Consequently, the FD methods are well suited for real-time implementations, for which TD methods could hardly be realistic owing to computational costs, but also for dealing, for example, with unstable models, which is rather common for military aircraft. In this case, no divergence of the internal simulations is to be feared since this technique do not proceed to TD integrations; the use of a stabilizing loop is thus avoided, which eliminates the risk of interactions between the stabilizing feedback and the identification process. It is also noteworthy that FD techniques can be beneficial to both OE and EE approaches, especially for real-time implementations, as far as the EE case is concerned; hence, the interest of FT regression has been highlighted in many publications [47]. Regarding TD algorithms, the only limitation (but not an insignificant one) results from the requirement to cope with linear or linearized models (at least locally valid).

These major application topics (model instability and online implementation) were explored by DCSD through two different research programs: with Dassault Aviation for identifying an unstable A/C, and during a long-term project jointly run by Onera and DLR between 2006 and 2010, named IMMUNE (*Intelligent Monitoring and Managing of Unexpected Events*). The objective of this project was to show the capability and viability of intelligent techniques for monitoring and handling the Flight Control Systems (FCS) in real time, to improve civil A/C safety and autonomy. The monitoring was based on several methods, including modern Fault Detection, Isolation and Estimation (FDIE) techniques and of course on-line identification. The handling of the detected events was contemplated by different reconfiguration or self-adapting techniques, based on Fault Tolerant Control (FTC) principles. Both actions are strongly dependent and therefore were linked via a supervisory architecture in charge of the decision making [9].

The FD identification method presented above can be useful both for event detection via the variation of aerodynamic parameters, and for event handling since an updated model is often required for indirect adaptation or FTC techniques [33]. In practice, it delivers a near real time estimation of the stability/control derivatives involved in the A/C modeling. For monitoring purposes, these estimates are compared to a set of reference values corresponding to the nominal behavior (non-faulty situation). In the framework of FDIE, using this method for diagnosis makes up a special class of model-based methods, the residuals referring to model parameters instead of the TD histories of measured variables, as is usually the case. Due to weak excitation signals and large residual errors (ordinary control signals resulting from pilot or autopilot orders are used), a measure of confidence is essential to the accommodation logic, but this measure can be easily computed via the standard deviation of the estimation errors, directly available from the FD method. Finally, FD identification is the central part of a monitoring process that also includes pre-processing and post-processing stages, respectively, to prevent and filter out inaccurate estimations. The scenarios used as benchmarks during IMMUNE involved actuator FDIE on the one hand and detection of icing accretion on the other hand. Results can be found in [18]. The computational feasibility of an onboard implementation was thus shown for this FD OE method. Owing to its characteristics, the algorithm requires a few iterations to converge and the memory requirements are limited thanks to a moving data windowing. The technique can estimate changes in the dynamics within a short delay, despite state and output noises.

State-space models for control design

Multivariable state-space models are required to design control laws using modern control techniques such as LQR/LQG, LPV/LFT, H2/H∞ [56]. They must provide an accurate description of the relationship between the surface control deflections and the output signals used by the controller. For a flexible aircraft, given the strong interaction between the FCS and the first aeroelastic modes, a suitable model for control purposes must include rigid-body and structural dynamics and represent the aircraft in an extended frequency range. Reduced order models can also be derived from those identified before applying control techniques [52]. Though preliminary knowledge may provide theoretical models that are appropriate for a first design iteration, model identification from in-flight data is then required for a fine analysis or tuning of the control law performance. Therefore, a two-step identification procedure depicted in figure 16 was developed by DCSD. The corresponding software developments were included in a toolbox called HARISSA and were successfully used by Airbus for the design of structural active control laws for A340-600 aircraft [34,35]. The two steps of the procedure consist in:

• Firstly, a discrete-time representation of the structural dynamics is determined from specific flight tests (typically frequency sweeps) thanks to the Eigensystem Realization Algorithm (ERA); ERA is one of the few available techniques permitting a multivariable state-space model to be derived from i/o data [34,65]. This representation includes only modes that are visible from the measurements. Then, it is converted to continuous-time and turned into a real block-diagonal form that provides a minimal parametric representation [4];

• Secondly, a state-space model of the flexible aircraft is obtained by gathering the structural and rigid-body linearized models, both in state-space form. The coupling is performed by simply adding the outputs of the two models. This merged model is used to initialize an OE approach relying on a Gauss-Newton algorithm in the FD, similar to the one described in the previous section (see also [18]). The identification is based on both usual rigid-body excitations and peculiar excitations dedicated to flexible modes. If it proves to be necessary, a preliminary estimation of the rigid-body model coefficients may be performed by a standard OE approach in the TD.

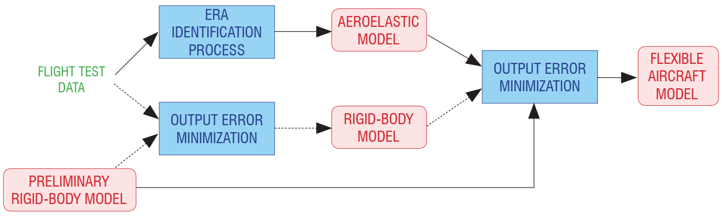


Figure 16 – General chart of the two-step identification procedure

MODEL VALIDATION

Estimation of unknown inputs and model corrections

Input estimation is a general process aimed at estimating the input uncertainties or the control orders of a given system, for which a mathematical model and some experimental responses are available and assumed accurate enough. Several tools have been developed to estimate various types of corrections (control surface deflections, aerodynamic coefficients, sidestick deflection, wind), which, once applied to aircraft inputs, could ensure a best match between the computed model responses and the measurements. This aspect (shown in red in figure 17) is the counterpart of parameter estimation (in blue) and data preprocessing (in green), which are aimed at correcting the model parameters or the measured outputs, respectively, assuming either a perfect knowledge of inputs and outputs on the one hand, or of inputs and model on the other hand.

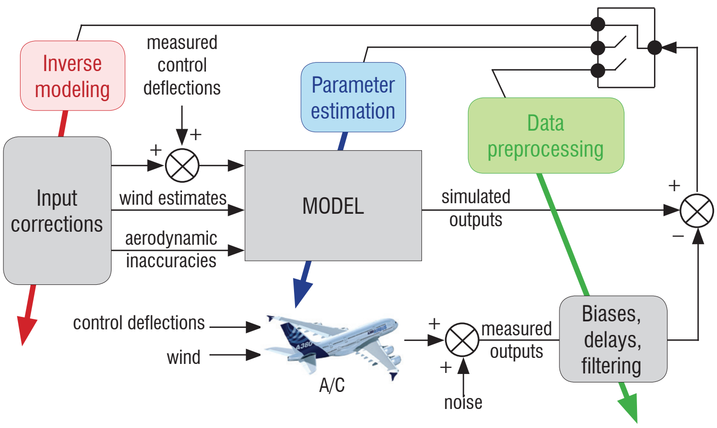


Figure 17 – Input estimation vs. parameter identification vs. data preprocessing

Thus, an estimation of some corrections related to the aerodynamic coefficients can be implemented as a preliminary step in an identification process based on an EE approach. In this case, the estimated corrections are computed from the pre-flight aircraft model and the analysis of the corrected aerodynamic coefficients can be useful to improve the structure of the aerodynamic modeling. Following the model update by EE, an additional estimation of input corrections can be performed to check the validity of the identified model. The new estimated corrections should be centered around 0 and their amplitudes should be kept small enough to ensure that a sufficiently accurate model is derived.

In such cases, whenever a state-space model of the aircraft is available, Kalman-Rauch smoothing is an efficient and well-suited method for this estimation problem. Several tools have been developed based on a KF, including the complete nonlinear A/C model. This technique has also been extended to the processing of tests including transitions between ground and flight phases, which lead to account for discontinuities in states or inputs. The basic principle of this method is described by the block diagram in figure 18, whereas the stochastic models involved in this method are described below:

Continuous time process model

$$\begin{cases} \dot{x} = f(x, u, \Delta C) \\ \Delta \dot{C} = \eta \end{cases}$$

Discrete time observation model

$$z_k = g(x_k, u_k, \Delta C_k) + \zeta_k$$

where x represents the aircraft state, u the inputs, ΔC represents the corrections related to the aerodynamic coefficient and η represents a Gaussian process noise, whereas z_k is the measurement vector and ζ_k is a Gaussian observation noise.

To represent the aerodynamic corrections, additional state variables are introduced, with dynamics governed by a random walk process. In principle, all process noises are assigned to the aerodynamic corrections, but their amplitudes depend on both the accuracy of the pre-flight model and the shape of the aircraft maneuver. Hence, standard deviations should be adjusted for every test. In order to automate this tuning which usually relies on user experience, an iterative technique has been designed by DCSD to estimate the variances of both process and measurement noises. This algorithm is aimed at guaranteeing the consistency between the theoretical and statistical standard deviations of the smoothing residuals.

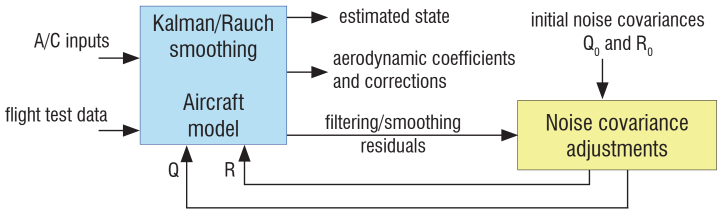


Figure 18 – Estimation of aerodynamic corrections by a filtering approach

QTG tests

For each new aircraft, manufacturers are in charge of providing training simulators with a set of validation tests approved by the aviation authorities. These tests are aimed at proving the ability of the simulator to replicate the real aircraft motion within the regulation tolerances. They are put together within the Qualification Test Guide (QTG) and provide a basis for the qualification of the simulators. However, a preliminary step is necessary for the QTG tests, before delivering them to the simulator manufacturers. It consists in a fine tuning of the simulation inputs (initial conditions, pilot inputs) in order to satisfy the requirements of the aviation regulations. If manually operated, this task can be very tedious and time-consuming depending on the type of test, especially for tests flown with the FCS activated. This is why DCSD has designed an efficient tool able to tune a set of various tests, automatically and within a reasonable amount of time.

The solution to this problem comes up against a number of difficulties:

- There is no analytical model of the A/C with the control laws available; the only model which can be used is the closed-loop simulation software, which excludes the use of estimation methods based on state-space representations because too many nonlinear and numerical solvers are involved;
- The model is strongly nonlinear and may be non-stationary during specific flight sequences, *e.g.*, an airplane flying with ground effect;
- The multivariable nature of the problem adds more complexity, so the question of a global processing or an axis by axis solution is raised;
- The solution must comply with strong input and output constraints. Moreover, some of these depend on the flight phase (approach, touchdown);

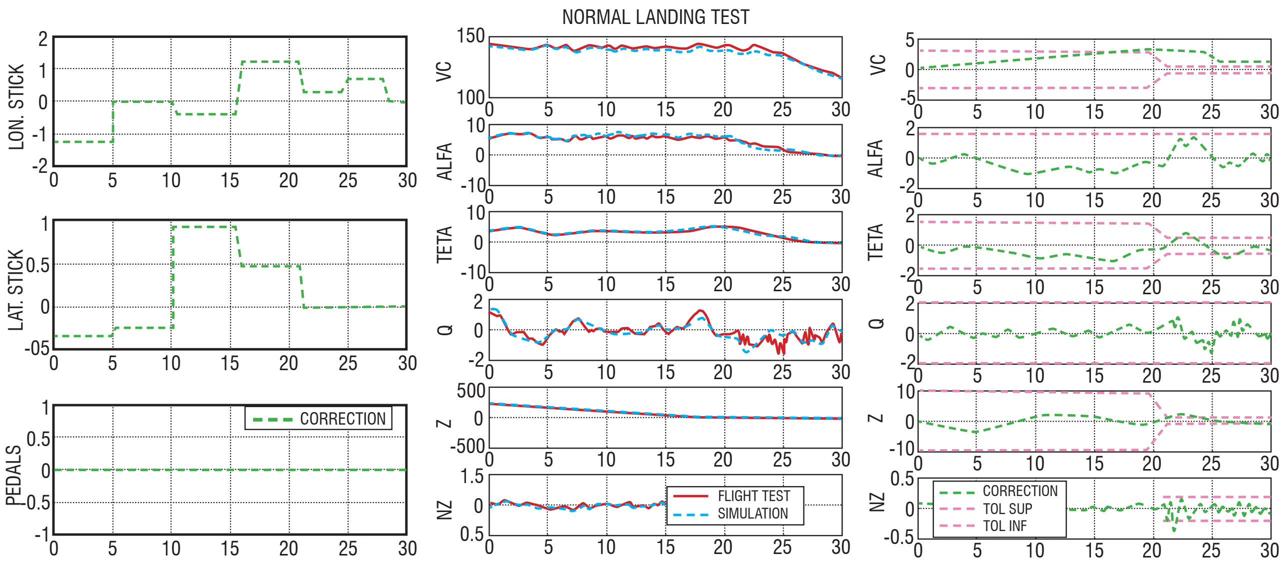


Figure 19 – Input corrections (sticks and pedals) for QTG tests

- If a solution exists, it is probably not unique since each solution satisfying the constraints is acceptable. That is why a solution minimizing the output energy will usually be favored;
- The computational cost per simulation is rather high, so that the total number of simulations should be very limited to keep the total CPU time acceptable.

The developed solution is based on a sequential processing of the air and ground stages. It has been validated from a challenging set of tests: normal landing, landing with crosswind and landing with one engine off. Optimization criteria peculiar to each phase are minimized by nonlinear optimization techniques to keep the discrepancies between simulation outputs and aircraft measurements within the tolerances. A first optimization step is devoted to the attitude and trajectory parameters, while a fine tuning of the landing gear and nose wheel touchdowns is achieved in a second optimization step. Various ways of parameterizing have been tested and compared, as regards to the corrections of the simulation inputs: multi-pulse signals including Haar or Walsh functions, multi-sine and Gaussian functions. The multi-pulse signals have turned out to be the best option. It doesn't matter whether the corrections of the longitudinal and lateral sticks are estimated simultaneously or not. Indeed, it appears that the two strategies yield very similar results. An illustration is given by figure 19.

Conclusion and prospects

Despite being non exhaustive, this survey reveals the variety of issues involved in the identification of aeronautical systems, illustrated by some of Onera's developments. It stresses the variety of the solutions required also, depending both on the available modeling and on the objectives. For instance, the structured form of modeling used for rigid A/C leads to the use of well-known and mastered techniques, EE/OE/FE-type, whether in TD or FD forms. On the other hand, the complexity of the aeroelastic physical models involved in the flexible case requires black-box type representations, only based on i/o data, to be sought. Though iterative least-squares are nowadays the favored algorithm to obtain these, subspace methods in the FD remain promising alternatives and they have been under consideration at Onera for several years.

Most of the current works related to rigid aircraft focuses less on developing new techniques than on adapting common ones to the requirements of the aeronautical industry. For the incoming A/C programs, the certification procedures should be achieved within a shorter and shorter time period, which implies that the length of the flight tests must be reduced. Hence, there is a great demand for developing new designs of experiments that would be more efficient, but also to assist the performing engineers in their tedious task while sifting through the whole set of flight data. As regards the latter, some advances are contemplated:

- Design of tools for making the user aware of the areas where the information provided by the data is too poor to obtain relevant results and accordingly where the pre-flight model should be preserved (a rather tricky matter in the multivariate case);
- Development of multiobjective algorithms, to take various types of criteria into account jointly, in both the TD and the FD;
- Merging the identification results computed under various flight conditions;
- Proposing incremental approaches to process new flight tests progressively, as soon as they become available, in order to improve the modeling without restarting from scratch;
- Taking advantage of new types of flight tests, requested by other A/C disciplines and teams, which extend to AoA-Mach-sideslip domains usually not covered by the tests devoted to the identification process.

Nevertheless, further efforts in dealing with the most complex aerodynamic nonlinearities are needed and, besides, parameter estimation in the presence of significant disturbances still raises a number of questions. As far as flexible A/C and flutter analysis are concerned, the current effort focuses on methods allowing several sensors and several control surfaces to be processed at the same time, the excitation signals being optimized to highlight the aeroelastic modes at best. The emphasis is also put on the robustness of the tools and their computational performances, owing to real-time processing requirements. To track the modes on-line, in order to prevent a critical behavior while expanding the flight domain, a Linear Parameter-Varying (LPV) modeling could be implemented in the future, with the A/C speed as a scheduling parameter ■

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Acronyms

CFD (Computational Fluid Dynamics)
FD (Frequency Domain)
TD (Time Domain)
ML (Maximum Likelihood)
KF (Kalman Filter)
EKF (Extended Kalman Filter)
UKF (Unscented Kalman Filter)
AoA (Angle of Attack)
SISO (Single Input-Single Output)
MIMO (Multiple Input-Multiple Output)
ED (Experimental Design)
OID (Optimal Input Design)
EE (Equation Error)
OE (Output Error)
FE (Filter Error)
LPV (Linear Parameter-Varying)
ERA (Eigensystem Realization Algorithm)
LP (Linear-in-their-Parameters)
LS (Least Squares)
OLS (Ordinary Least Squares)
WLS (Weighted Least Squares)
IV (Instrumental Variable)
NN (Neural Network)
RBFN (Radial Basis Function Network)
MLP (Multi-Layered Perceptron)
LLM (Local Linear Model)
PSO (Particle Swarm Optimization)
FT (Fourier Transform)
FFT (Fast Fourier Transform)
FCS (Flight Control System)
FDIE (Fault Detection, Identification and Estimation)
FTC (Fault Tolerant Control)
QTG (Qualification Test Guide)
IMMUNE (Intelligent Monitoring and Managing of UNexpected Events)

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Dynamical Medium (Large)-Scale Model Reduction and Interpolation with Application to Aircraft Systems

Although the need for even more accurate system, phenomena and process modeling is required in order to reduce development time and costs, the number of variables linear and non-linear optimization tools can handle is still a practical and theoretical limiting factor. This is especially true in aircraft dynamical performance analysis, monitoring and control design, where dynamical models are accurately designed at varying local flight configurations, in order to handle flexible modes, aerodynamic delays, etc., leading to high-dimensional problems [5]. Although Onera has a well established tradition of proposing complete and efficient tools for optimizing controllers and analyzing dynamic system performances through the use of Linear Fractional Representation (LFR) mathematical objects [2, 15, 22], recent growth in the dimensions of models has led to strong time and computational limitations when using these tools. The aim of this paper is to give an overview of the solutions developed within Onera **to approximate a set of large-scale dynamical models with a parameterized LFR lower order model**, which can be used in place of the original ones to effectively synthesize control laws and achieve performance analysis.

Introduction and main problem

Motivations and challenges in aeronautics

In many areas of engineering (*e.g.* aerospace, automotive, biology, circuits…), dynamical systems are the basic framework used for modeling, control and analysis of a large variety of systems and phenomenon. Due to the growth in the use of dedicated and accurate computer-based modeling design software, numerical simulations have been increasingly used to simulate complex systems or phenomenon and shorten both development time and cost. However, the need for enhanced accuracy of the models has led to an increasing number of variables and resources to be handled at the price of a high and expensive computational cost. Moreover, from the control engineer point of view, modern analysis (*e.g.* LPV H_∞ and H_2 norm computation, μ-analysis…) and synthesis (*e.g.* H_∞, H_2 control…) tools [2, 4, 8, 9, 22] become drastically inefficient for such high-dimensional dynamical systems (see figure 1) [1].

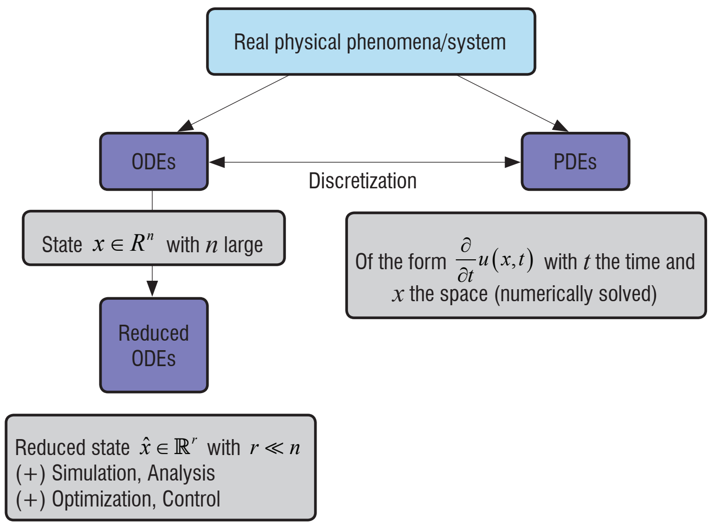


Figure 1 – Illustration of the model reduction paradigm

These remarks are especially true in the flight dynamics domain where aircraft are locally modeled (*i.e.* at each flight and mass point) with high fidelity tools to account for the flexible modes and aeroelastic delays (see *e.g.* [5]).

As an illustration, let us consider figure 2, in which the frequency responses of an industrial longitudinal aeroelastic commercial aircraft are plotted for varying flight points (MACH / Calibrated air speed configurations). The model considered has 3 inputs (the ailerons deflection, the elevator deflections and the vertical wind disturbance) and 3 outputs (the vertical load factor, the bending moments at the tail horizontal plan and at the wing/fuselage positions). This model also includes actuators and a severe von-Karman wind disturbance model. It is worth noting that the entire model has about 300 states and that the system behavior is flight conditions dependent (see also, a very interesting paper on aircraft modeling [5]).

Because of this complexity, the resulting control engineer problem is large and configuration/flight point dependent. More specifically, the high numbers of variables and dynamics lead to two major problems for numerical and control engineers:

- An increase in simulation time and, eventually, in the difficulty of analyzing the model's properties with respect to uncertainties, parameter variations, nonlinearities…;
- The difficulties of controller synthesis. In practice, modern control methods (such as LQG, Robust, MPC…), use the dynamical system model directly and employ optimization methods (*e.g.* descent, LMI, non-smooth…) to synthesize the controllers [2, 22].

Consequently, **the model reduction and interpolation stage**, linking the modeling and the control law design, aims to achieve the following main objectives (see also the very relevant work of Antoulas [1]):

- To **speed up the simulation** in the validation stage, using simpler models, while preserving the most significant system dynamics and properties (*e.g.* frequency response, stability, structure…);
- To **efficiently use the numerical control tools** in order to synthesize controllers in a cleverer manner and thus focus on the controller structure for implementation purposes. Note that most modern control approaches lead to controllers that are considerably more complex than truly needed (mainly because of the initial dimensions of the model);
- To **describe the nonlinear model over the entire parametric domain** (*e.g.* flight point and mass configurations), even if the model is only provided at local configurations.

Mathematical problem definition and Onera approach

Starting from a set of medium (large) scale Linear Time Invariant (LTI) models describing a complex system at frozen configurations, the problem tackled in this paper consists of obtaining a reduced-order Linear Parameter Varying (LPV) model of suitable form, from which a Linear Fractional Representation (LFR) can be built to be used in place of the original LTI models. This objective is formalized in problem 1 (see also [21]).

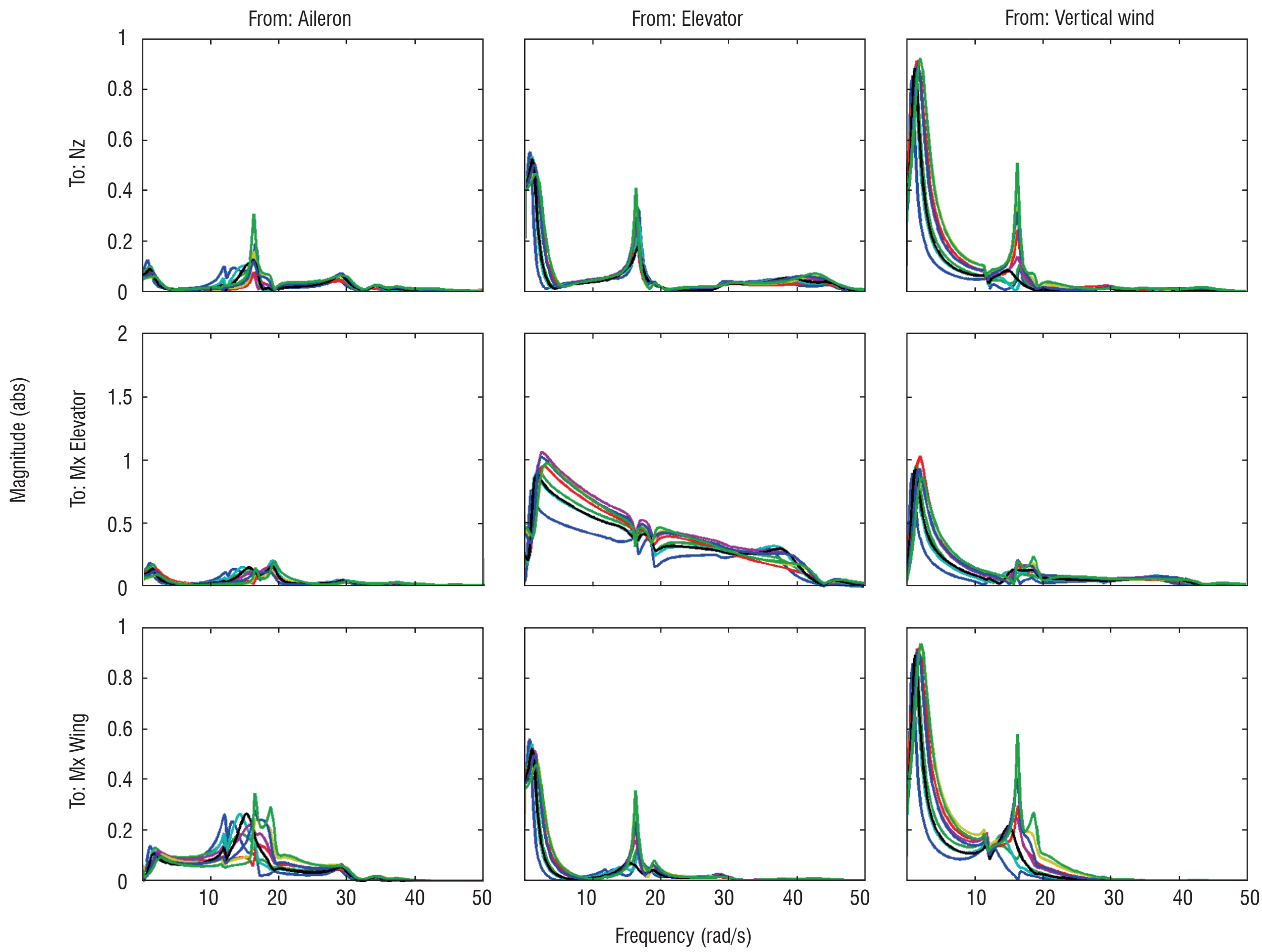


Figure 2 – Frequency response for varying flight configurations (in MACH / Calibrated air speed)

Problem 1 - Multi-models approximation and interpolation

Let us consider a set of N dynamical system models of order n (e.g. defined by n-ODEs), corresponding to different parametric configurations (e.g. flight point, tank filling...), described as follows:

$$G_i : \begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i u(t) \\ y(t) = C_i x_i(t) \end{cases}, \text{ where } i \in \{1,\dots,N\}$$

The objective is to find a parameterized model of order $r \ll n$, of the form,

$$\hat{G}(\delta) : \begin{cases} \dot{\hat{x}}(t) = \hat{A}(\delta)\hat{x}(t) + \hat{B}(\delta)u(t) \\ \hat{y}(t) = \hat{C}(\delta)\hat{x}(t) \end{cases}, \text{ where } \delta \text{ varies within a bounded compact set}$$

that well approximates the original system at each local model configuration, and the frequency responses and eigenvalues of which evolve smoothly as the parameters vary.

A two step procedure is adopted to solve problem 1: (i) **local model reduction**, approximating the original local system model with a lower order one, while minimizing the mismatch error and preserving stability, and, (ii) **model interpolation** in order to construct a Linear Fractional Representation (LFR) on which control and analysis can be achieved. The rest of the paper is organized as follows: § "Approximation of large-scale LTI models" presents some literature approximation techniques and points out Onera's contributions. Then, interpolation issues and Onera's contributions to complete this step are presented in § "Algorithm for flexible aircraft LFT modeling". Then, § "Industrial application" presents very successful results from combining the reduction and interpolation phases, applied to an industrial aircraft model. Finally, we conclude and indicate directions for further development.

Approximation of large-scale LTI models

This section presents the model reduction step. This step is used to reduce the original model's complexity while keeping the model's main properties.

Preliminaries and problem formulation

There are two main families in the LTI model reduction field: (i) the projection based methods and (ii) the non-projection based ones. While the second methods are not well appropriated for a large-scale model [1, 20], the former methods clearly exhibit the best performances and will thus be considered in what follows. Mathematically, the problem considered in this section is given as in Problem 2.

Problem 2 - Projection-based linear dynamical systems approximation

Let us consider a MIMO dynamical model $G := (A, B, C)$ of an aircraft's dynamics at frozen configurations, defined by n-ODEs, as follows:

$$G : \begin{cases} \dot{x}(t) = Ax(t) + Bu(t) \\ y(t) = Cx(t) \end{cases}$$

where $A \in \mathbb{R}^{n\times n}, B \in \mathbb{R}^{n\times n_u}, C \in \mathbb{R}^{n_y\times n}$

The projection-based model reduction problem consists of finding $V,W \in \mathbb{R}^{n\times r}$, where $W^T V = I_r$ ($r << n$), such that the reduced order model $\hat{G} := (\hat{A},\hat{B},\hat{C})$, defined as,

$$\hat{G} : \begin{cases} \dot{\hat{x}}(t) = \hat{A}\hat{x}(t) + \hat{B}u(t) \\ \hat{y}(t) = \hat{C}\hat{x}(t) \end{cases}$$

where $\hat{A} = W^T AV \in \mathbb{R}^{r\times r}, \hat{B} = W^T B \in \mathbb{R}^{r\times n_u}$ and $\hat{C} = CV \in \mathbb{R}^{n_u\times r}$, well approximates the original system, in the sense of a given metric.

Considering problem 2, the classical manner to assess **the quality of an approximation** is to consider the system's error by mean of a mathematical measurement. To do so, let us simply introduce the classical metrics widely used in the numerical and control communities, *i.e.* [1, 11]:

- The relative "mismatch error" metric (in %), based on the H_2 norm, defined as:

$$J_{H_2} = 100\frac{\left\|H(s) - \hat{H}(s)\right\|_{H_2}}{\left\|H(s)\right\|_{H_2}}$$

where $\left\|H(j\omega)\right\|_{H_2} = \sqrt{\frac{1}{2\pi}\int_{-\infty}^{\infty} Tr\left(H(j\omega)^* H(j\omega)\right)d\omega}$

- The relative "worst case" error metric (in %), based on the H norm, defined as:

$$J_{H_\infty} = 100\frac{\left\|H(s) - \hat{H}(s)\right\|_{H_\infty}}{\left\|H(s)\right\|_{H_\infty}}$$

where $\left\|H(j\omega)\right\|_{H_\infty} = \sup_{\omega\in\mathbb{R}} \bar{\sigma}\left(H(j\omega)\right)$

In the model approximation framework, the objective is thus to reduce these errors. While the latter is practically very complex to achieve for large (medium) scale models due to the (iterative) nature of the H_∞ norm computation, when considering the former, first-order optimality conditions can be characterized and satisfied, practically, thanks to the celebrated Wilson conditions (see [13, 23, 24, 25, 26]).

(Non exhaustive) state of the art in the dynamical model approximation field

Methods that can be used to meet the Wilson first-order optimality conditions [25] have been widely explored and still are of great interest in both the numerical and control communities. Significant results in this field propose an iterative procedure for converging toward a near optimal condition. The underlying idea is to iteratively construct the projectors $V,W \in \mathbb{R}^{n\times r}$ using either the **Lyapunov and Sylvester-like** approaches [17, 26] or the **Tangential (Krylov)** ones [13, 23].

Tangent (Krylov) approaches

More specifically the following techniques, derived from the Tangential (Krylov)-like approaches, have retained a lot of attention in the recent years since they do obtain very nice results in practice and provide computational effectiveness:

- The Iterative Rational Krylov Algorithm (IRKA), initially set for SISO systems [13] which produces excellent results on benchmarks [7] but does not guarantee stability (unless implementing specific restart techniques). Later, in [3], the authors extended it to MIMO systems, with a complex Trust Region algorithm which guarantees convergence and preserves stability;
- At the same time, the Iterative Tangential Interpolation Algorithm

(ITIA) for MIMO systems, suggested in [23, 24], was developed to handle the MIMO case. Indeed, the ITIA, developed in [10, 23] is similar to the MIMO IRKA. Like the previous one, this procedure has proved to be effective on many classical benchmarks [7] but does not preserve stability, *a priori.*

The underlying idea of these methods is the moment matching. The moments are defined as follows.

Definition 1 - System moments

Let $H(s)=C(sI_n-A)^{-1}B$ be a complex valued MIMO rational transfer function. The system moments η_i, around the complex shift σ, are defined as a Laurent series given as follows,

$$\eta_i = -C(\sigma I_n - A)^{-(i+1)}B$$

and verify,

$$H(s)=\sum_{i=0}^{\infty}\eta_i(s-\sigma)^i$$

Because of the A matrix power, the moments computation is usually ill-conditioned and explicit moment matching is thus numerically impossible to achieve [20]. Consequently, the fact that the construction of Krylov subspaces allows for moment matching without computing them explicitly is used. Moreover, Krylov subspaces can be efficiently constructed through Arnoli-like procedures, very cheap from the computational point of view [1, 12, 20]. The main result of the moment matching, by construction of Krylov subspaces, is formulated in the following theorem (see *e.g.* [1, 13] and references therein).

Theorem 1 - Rational Krylov subspace and moment matching

Let $H(s)=C(sI_n-A)^{-1}B$ be a complex valued MIMO (n_u inputs, n_y outputs) rational transfer function, and $\sigma_k \in \mathbb{C}$ be k interpolation points such that $(\sigma_k I - A)$ is invertible, if,

$$\begin{cases}\bigcup_{k=1}^{K}\mathbb{K}_r\left((\sigma_k I-A)^{-1},(\sigma_k I-A)^{-1}B\right)\subseteq span(V)\\ \bigcup_{k=1}^{K}\mathbb{K}_r\left((\sigma_k I-A)^{-*},(\sigma_k I-A)^{-*}C^T\right)\subseteq span(W)\end{cases}$$

where $\mathbb{K}_r(A,B)=\left[B,AB,...,A^{r-1}B\right]$ stands for the Krylov subspace of order r. Then, moments of the original and reduced models satisfy

$$\hat{\eta}_{\sigma_k}^{(j_k)}=\eta_{\sigma_k}^{(j_k)} \;\; for \;\; j_k=0,...,\left\lfloor\frac{r}{n_u}\right\rfloor+\left\lfloor\frac{r}{n_y}\right\rfloor-1$$

Based on this theorem, recent results within the numerical and control communities have provided proof and algorithms that can be used to meet the Wilson H_2 optimality conditions through the construction of iterative projectors (for more details, see [20, 25] and references therein).

Sylvester (and Lyapunov) like approaches

In parallel to the Tangent (Krylov)-like approaches, other techniques have been developed from the Sylvester and SVD approaches to approximate MIMO LTI systems (without always aiming at guaranteeing H_2 first-order optimality conditions), *e.g.*:

- Balanced Truncation (BT), which is often considered as the gold standard since it preserves stability, provides a bound on the error and a nearly optimal H_2 error. The drawback is that it may fail in practice when the system order is too large, because of the need to solve two Lyapunov equations [11, 27];
- The Low Rank Square Root Method (LRSRM), which is a modification of the BT approach, is applicable for large-scale models but does not guarantee the preservation of stability [17];
- Dominant Subspaces Projection Model Reduction (DSPMR), which is a heuristic approach that can be used to handle large-scale systems, without guaranteeing stability;
- The Two-Sided Iterative Algorithm (TSIA), which iteratively solves two Sylvester equations, has been shown to be equivalent to the tangential interpolation. This procedure guarantees stability and provides nice results for medium-scale problems but it suffers of two main drawbacks: first, it requires a good projector initialization to converge, and secondly, no stopping criterion has been described so far [26].

This second family of methods basically consists of solving either Lyapunov or Sylvester equations. As an illustration, Lyapunov-based approaches consist of solving the following equations:

$$\begin{cases}AP+PA^T+BB^T=0\\ A^TQ+QA+C^TC=0\\ P=Q=diag(\sigma_1,...,\sigma_n)\end{cases}$$

where $(\sigma_1,...,\sigma_n)$ are the matrix singular values

Then, states with high energy are kept, while the others are eliminated. When considering the Sylvester like approaches, the problem consists of solving a lower order equation of the form [26],

$$\begin{cases}AV+V\Sigma_\sigma+BR=0\\ W^TA+\Sigma_\mu^TW^T+L^TC=0\end{cases}$$

Many other methods exist, but the above ones catch our attention because of their efficiency. The main drawback on these approaches concerns the resolution of such equations.

Mixed approaches & Onera contribution

Nowadays, another family of methods is being increasingly explored: mixed ones. These methods combine the advantages of both methods. For deeper insight, readers are invited to refer to [12, 19]. Recently, Onera has made a contribution that is illustrated in Box 1.

Industrial aircraft application & comparison of methods

In this section, the model reduction techniques are applied to an industrial problem. The model considered is an industrial longitudinal aeroelastic model at varying flight points, as illustrated in figure 2 [20]. It is worth emphasizing that approximating (and controlling) such system is a challenging task since the model's order is about 300, the conditioning number is very high and numerous badly damped modes are present. The ISTIA approximation procedure is used on this industrial flexible aircraft model, and benchmarked with respect to the ITIA and the BT methods (note that BT is the one implemented in very efficient commercial computing software). In figure 3, the ε_{H_2} error (mismatch error) of models approximated with the BT, ITIA and ISTIA are plotted as a function of the approximation order r for a model at one single flight point.

Box 1 - Onera contribution (ISTIA) and tool developments

Based on [12] and [23], in [19], a new hybrid methodology has been proposed to allow for accurate LTI model approximation while preserving system stability. In the **MORE Toolbox**[1] very recent methods in the field of large-scale systems approximation, extracted both from the literature [12, 13 26] and from the project carried out within the laboratory [19, 20], have been implemented. One contribution is the definition and the numerical implementation of the SVD Tangential Interpolation Algorithm (ISTIA) [19], summarized as follows:

Algorithm ISTIA: Iterative SVD-Tangential Interpolation Algorithm [19]

Require: $A \in \mathbb{R}^{n\times n}, B \in \mathbb{R}^{n\times n_u}, C \in \mathbb{R}^{n_y\times n}, \left[\sigma_1^{(0)},\ldots,\sigma_r^{(0)}\right] \in \mathbb{C}^r, \left[\hat{b}_1,\ldots,\hat{b}_r\right] \in \mathbb{C}^{n\times r}, \varepsilon > 0$

1 Construct $V = span\left((\sigma_1^{(0)} I - A)^{-1} B\hat{b}_1, \ldots, (\sigma_r^{(0)} I - A)^{-1} B\hat{b}_r\right)$

2 Solve $A^T Q + QA + C^T C = 0$ in Q

3 Compute $W = QV(V^T QV)^{-1}$

4 While $\left|\sigma^{(i)} - \sigma^{(i-1)}\right| > \varepsilon$ Do

5 $i \leftarrow i+1$ and $\hat{A} = W^T AV, \hat{B} = W^T B$

6 Compute $\hat{A}X = diag\left(\lambda(\hat{A})\right)X$

7 Compute $\left[\hat{b}_1,\ldots,\hat{b}_r\right] = X^{-1}\hat{B}$

8 Set $\sigma^{(i)} = -\lambda(\hat{A})$

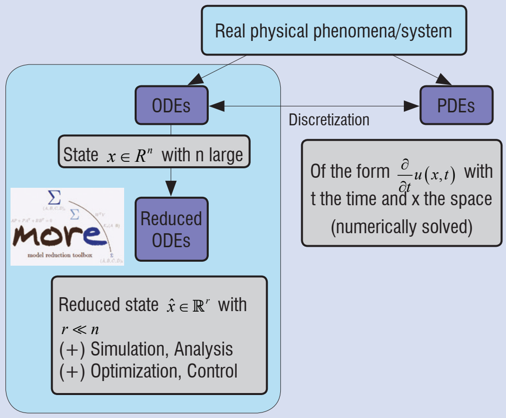
9 Construct $V = span\left((\sigma_1^{(i)} I - A)^{-1} B\hat{b}_1, \ldots, (\sigma_r^{(i)} I - A)^{-1} B\hat{b}_r\right)$

10 Compute $W = QV(V^T QV)^{-1}$

11 EndWhile

12 Construct $\hat{\Sigma} := (W^T AV, W^T B, CV)$

Ensure: $\hat{\Sigma} := (W^T AV, W^T B, CV)$ stable and partial H_2 optimality conditions



This algorithm has very nice theoretical and practical properties, such as, an almost H_2 optimal model approximant of the original one, while preserving stability at each step. The stopping criterion allows limiting the accuracy of the optimality criteria. Practically, the parameter is chosen small (*e.g.* 10^{-2}). It has been successfully applied on many large-scale models and on industrial flexible aircraft models, showing enhanced performances with respect to the classical techniques [19, 21]. On the following figure B1-1, the algorithm evolution is illustrated as it iterates, showing the mismatch error decrease and the interpolation points selection. Video - http://www.aerospacelab-journal.org/al4/scale-model-reduction-and-interpolation-with-application-to-aircraft-systems

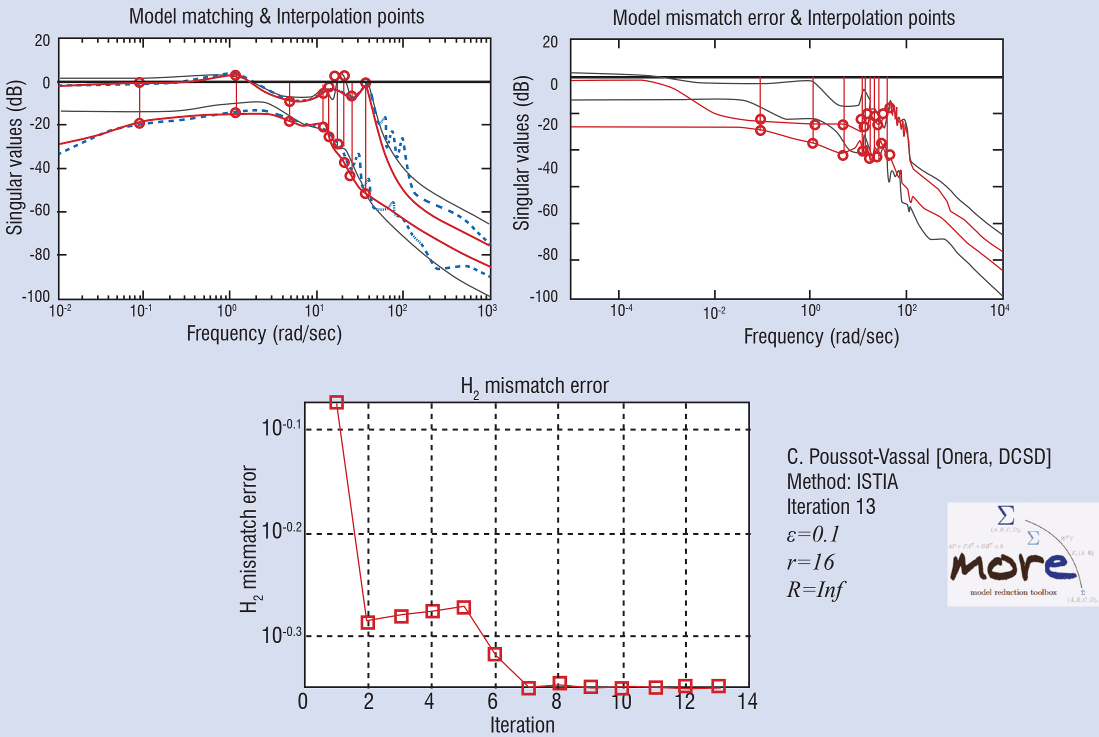


Figure B1-1 – Illustration of the algorithm evolution. Top left: frequency response (original, dashed blue / reduced, solid red). Top right: mismatch relative error (initial, solid black / reduced, solid red). Bottom left: mismatch error ε_{H_2} as a function of the iteration i.

[1] The MORE Toolbox - stands for MOdel REduction Toolbox (http://www.onera.fr/staff-en/charles-poussot-vassal) - is a dedicated medium(large)-scale LTI dynamical model approximation toolbox, developed within the Onera DCSD, by C. Poussot-Vassal.

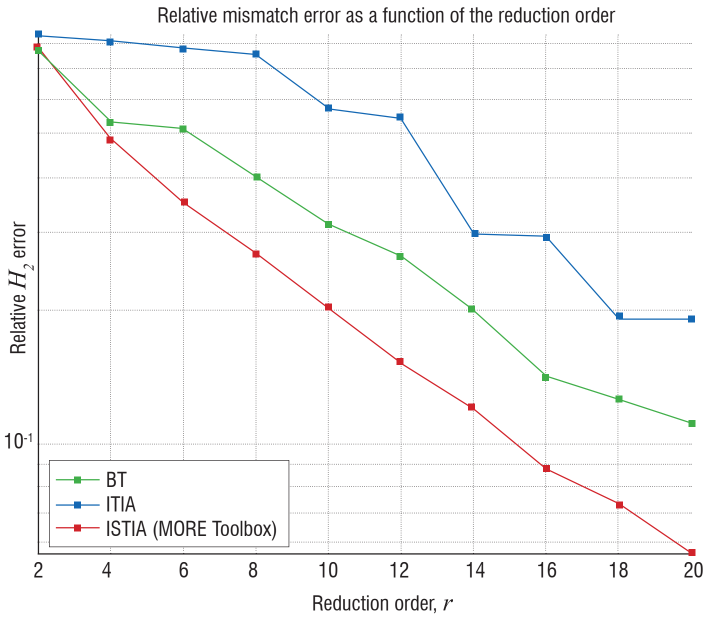


Figure 3 – Mismatch relative error (ε_{H_2}) as a function of the reduction order r, for one single flight configuration.

With reference to figure 3 it appears that the proposed ISTIA method outperforms the ITIA and BT approaches in terms of error mismatch in all situations. Next, figure 4 compares the frequency responses (left) and the eigenvalues locations (right) between the original and reduced models, with order 20, obtained with the ISTIA technique. Looking at this figure, it is clear that a good fit in terms of frequency response and pole location is achieved. This last point is crucial for engineers who are familiar with the physical meaning of model modes. Indeed, this specific feature is one of the advantages of the interpolation-based techniques, because they can focus on specific behaviors through the choice of initial interpolation points.

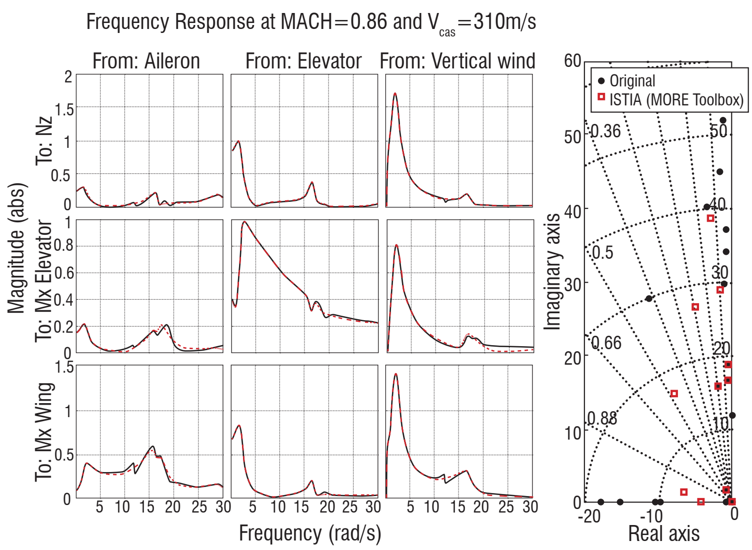


Figure 4 – Left: frequency response comparison of the original of order 286 (solid black) and approximated model of order 20 with ISTIA (dashed red). Right: eigenvalues of the original (black rounds) and approximated model with ISTIA (solid squares)

By performing this local reduction for every local LTI model, a collection of reduced order models are produced which can then (almost) be interpolated in order to build a parameterized model, describing the aircraft's behavior over the entire flight domain.

Algorithm for flexible aircraft LFT modeling

Based on the reduced order models, interpolation is now performed in order to generate an LFR model.

State coordinate transformation for state vector consistency

At this stage, the N reduced order models are available with the same number of modes which are not always of the same nature.

Now before interpolating the state space matrices, a state basis must be found that ensures that these matrices are consistent in terms of states whatever the flight point index i. More precisely, after the state matrices have been interpolated, the result must be regular modal trajectories as well as variations in frequency responses with respect to the flight parameters vector δ (see figure 5). This is an efficient test for state vector consistency.

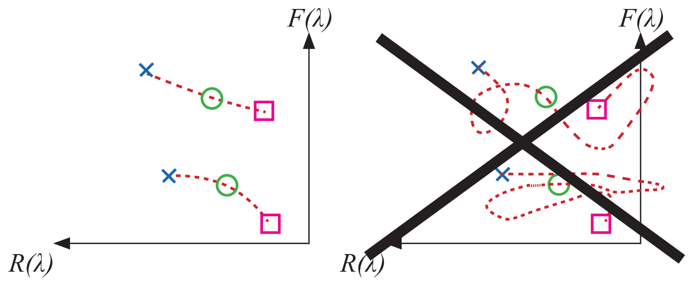


Figure 5 – Strong constraint: modal trajectories regularity

Our research showed that the characteristic polynomial of the models (1) is of deep interest as regards the modal trajectories regularity constraint. This phenomenon can be explained by the physical nature of this polynomial's coefficients (1) that are directly linked to the transfer function, and even more directly with the physical differential equations of the flexible aircraft.

$$d(s) = det(sI - A)$$
$$d(s) = s^{n_z} + c_{n_z-1}s^{n_z-1} + \cdots + c_1 s + c_0 \qquad (1)$$

The state basis linked with the characteristic polynomial is the companion basis, in which the A matrix has the form:

$$A_i^{comp} = \begin{pmatrix} 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \ddots & \vdots \\ \vdots & \vdots & \cdots & 1 & 0 \\ 0 & 0 & \cdots & 0 & 1 \\ -c_0^i & -c_1^i & \cdots & \cdots & -c_{n_z-1}^i \end{pmatrix}$$

This companion state basis is known to provide badly-conditioned state matrices. So the A_i^{comp} matrices must be regularized via a scaling matrix T to balance the coefficients' values, while keeping the same eigenvalues [29]. The same scaling is applied to all models (*i.e.* $\forall i$ for consistency); a regularized companion matrix A_i^{compr} is then obtained:

$$A_i^{compr} = T^{-1} A_i^{comp} T$$

The scaling matrix T is computed for matrix A_i^{compr} so that it has the same rows and columns norms, as far as possible. More precisely, T is a diagonal matrix assembles integer powers of two on its diagonal, to avoid round off errors:

$$T = diag(2^{k_1}, \ldots, 2^{k_{n_z}})$$

in which $(k_p)_{p\in[1,n_x]}$ are the aforementioned integers, independent of the i index (flight point index).

The final regularized companion matrix A_i^{compr} is then:

$$A_i^{compr} = \begin{pmatrix} 0 & 2^{k_2-k_1} & 0 & 0 \\ 0 & 0 & \ddots & \vdots \\ 0 & 0 & \cdots & 2^{k_{n_z}-k_{n_z-1}} \\ -cr_0^i & -cr_1^i & \cdots & -cr_{n_z-1}^i \end{pmatrix} \quad (2)$$

where cr are the regularized characteristic polynomial coefficients.

Now the state space matrices corresponding to this regularized companion form (2) must be computed. To do so, the key step consists of linking the A_{compr} matrix with the initial A matrix by resorting to its modal form. Indeed, both matrices have one feature in common: their eigenvalues.

So, first the *(A,B,C)* model is expressed in the modal basis then the basis change matrix P_{mod} is computed so that:

$$\begin{cases} A_{mod} = P_{mod}^{-1} A P_{mod} \\ B_{mod} = P_{mod}^{-1} B \\ C_{mod} = C P_{mod} \end{cases}$$

The P_{mod} matrix has the form:

$$P_{mod} = P_{modc} P_{cr} = P_{modc} \begin{pmatrix} 1 & j & 0 & 0 & 0 \\ 1 & j & 0 & 0 & 0 \\ 0 & 0 & \ddots & 0 & 0 \\ 0 & 0 & 0 & 1 & -j \\ 0 & 0 & 0 & 1 & j \end{pmatrix}$$

in which P_{modc} actually assembles the eigenvectors of A. Then, the same process is applied to A_{compr} matrix to get its modal form:

$$A_{mod} = P_{mod2}^{-1} A_{compr} P_{mod2}$$

The P_{mod2} basis change matrix has the same form as P_{mod} (its expression holds the eigenvector matrix of A_{compr} this time). For both basis changes, it can be shown that their generic expressions are:

$$P_{mod} = P_{modc} T_\Delta P_{cr}$$
$$P_{mod_2} = P_{modc_2} T_{\Delta_2} P_{cr}$$

where T_Δ and $T_{\Delta 2}$ are free (diagonal) scaling providing additional degrees of freedom and P_{modc} and P_{modc2} are matrices of eigenvectors of A. The latter can be used to help with the forthcoming state matrices interpolation (to improve the companion state matrices numerical conditioning or minimize their variations from one flight point to another).

Finally, the previous steps are summed up to compute the final basis change P such that:

$$\begin{cases} A_{compr} = P^{-1} A P \\ B_{compr} = P^{-1} B \\ C_{compr} = C P \end{cases} \quad (3)$$

We have:

$$\begin{aligned} A^{mod} &= P_{mod}^{-1} A P_{mod} &&= \left(P_{modc} T_\Delta P_{cr}\right)^{-1} A P_{modc} T_\Delta P_{cr} \\ &= P_{mod_2}^{-1} A^{compr} P_{mod_2} &&= \left(P_{modc2} T_{\Delta_2} P_{cr}\right)^{-1} A^{compr} P_{modc2} T_{\Delta_2} P_{cr} \end{aligned}$$

from which the A_{compr} matrix can be expressed with respect to the A matrix :

$$A^{compr} = \left(P_{modc2} T_{\Delta_2} P_{cr}\right)\left(P_{modc} T_\Delta P_{cr}\right)^{-1} A \left(P_{modc} T_\Delta P_{cr}\right)\left(P_{modc2} T_{\Delta_2} P_{cr}\right)^{-1} \quad (4)$$

Through identification using equation (3) and (4) the final basis change matrix is obtained:

$$P = P_{modc} T_\Delta T_{\Delta_2}^{-1} P_{modc2}^{-1}$$

Models interpolation and LFT modeling

Interpolation

The state space matrices are interpolated in their regularized companion form, through a multivariate polynomial structure $(p_j(\delta))_{j\in[1,N_t]}$. This problem can be easily solved with a least squares algorithm.

LFT realization

Once the interpolation structure is known, the LFT is simply obtained with the generalized Morton's method [16] that is implanted in the LFR toolbox (function **gmorton.m** [15]). This method is the generalization of the Morton's method to a polynomial expansion, and it relies on a singular value decomposition of each matrix coefficient.

Validation of the LFT

In order to assess the LFT accuracy, three criteria are defined: one evaluates the LFT modal matching with the reference models (5), and the other two are the $H\infty$ (6) and H_2 (7) frequential criteria for the frequency matching assessment.

$$\varepsilon_{modal} = \max_{i\in[1,N]} \left(\frac{\sum_{k=1}^{n_z} \left|\lambda_k^i - \lambda_k^{ref,i}\right|}{\sum_{k=1}^{n_z} \left|\lambda_k^{ref,i}\right|} \right) \quad (5)$$

where λ_k^i is the LFT's k-th mode at flight point number i and $\lambda_k^{ref,i}$ refers to the corresponding reference model $G_i(s)$.

$$\varepsilon_{H\infty} = \max_{i\in[1,N]} \left(\frac{\overline{\sigma}\left(\Delta F_i(jw)\right)}{\overline{\sigma}\left(G_i(jw)\right)} \right) \quad (6)$$

in which $\Delta F_i(j\omega) = (F_u(M(j\omega),\Delta^i) - G_i(j\omega))$ and $\overline{\sigma}$ is the maximum singular value on the pulsation continuum (H_∞ norm).

$$\varepsilon_{H_2} = \max_{i\in[1,N]} \left(\sqrt{\frac{1}{2\pi} \frac{\sum_j trace\left(\Delta F_i^*(jw_j) \Delta F_i(jw_j)\right)\Delta w_j}{trace\left(G_i^*(jw_j) G_i(jw_j)\right)}} \right) \quad (7)$$

where $\Delta\omega_j = (\omega_{j+1} - \omega_j)$

In depth validation is of course necessary to check both modal and frequential behaviors of the LFT on the whole model continuum. This step will be illustrated in the applicative example.

Input/Output error minimization

If the *I/O* error is not satisfactory, it can be minimized with a biconvex optimization. This algorithm is an extension to the LFT case of the one previously mentioned in paragraph 2. In this situation, the minimized criterion depends on the frequency error between the LFT and the reference models:

$$\Delta F_i(jw) = \left(F_u\left(M(jw), \Delta^i\right) - G_i(jw)\right)$$

Let us recall the state representation of an LFT:

$$\begin{cases} x = Ax + B_1 w + B_2 u \\ z = C_1 x + D_{11} w + D_{12} u \\ y = C_2 x + D_{21} w + D_{22} u \end{cases}$$

The LFT frequency response is then (the model index i is dropped for simplicity):

$$F_u\left(M(jw), \Delta\right) = C(\Delta) Y(jw, \Delta) B(\Delta) + D(\Delta)$$

with $Y(jw,\Delta) = \left(jwI - A(\Delta)\right)^{-1}$, $A(\Delta) = A + B_1 X_\Delta C_1$,

$B(\Delta) = B_2 + B_1 X_\Delta D_{12}$, $C(\Delta) = C_2 + D_{21} X_\Delta C_1$,

$D(\Delta) = D_{22} + D_{21} X_\Delta D_{12}$, $X_\Delta = \Delta\left(I - D_{11}\Delta\right)^{-1}$

Hence the two expressions of the frequency error are:

$$\Delta F(jw) = H_{BD}\begin{pmatrix} B_2 \\ D_{12} \\ D_{22} \end{pmatrix} - G(jw) = \left(c_2 D_{21} D_{22}\right) H_{CD} - G(jw)$$

with $H_{BD}^T(jw) = \begin{pmatrix} Y^T(jw,\Delta) C^T(\Delta) \\ X_\Delta^T\left[B_1^T Y^T(jw,\Delta) C^T(\Delta) + D_{21}^T\right] \\ I \end{pmatrix}$

and $H_{CD}(jw) = \begin{pmatrix} Y(jw,\Delta) B(\Delta) \\ X_\Delta\left[C_1 Y(jw,\Delta) B(\Delta) + D_{12}\right] \\ I \end{pmatrix}$

Back with the models indices *i.e.* i, each term of both H_2 criteria to be minimized:

$$J_{\Delta F \bullet \Delta F} = \sum_i \sum_i trace\left(\Delta F_i^*(jw_j) \Delta F_i(jw_j)\right)\left(w_{j+1} - w_j\right)$$

$$J_{\Delta F \Delta F \bullet} = \sum_i \sum_i trace\left(\Delta F_i(jw_j) \Delta F_i^*(jw_j)\right)\left(w_{j+1} - w_j\right)$$

has the following quadratic structure:

$$trace\left(\Delta F_i(jw_j) \Delta F_i^*(jw_j)\right) = c_{i,j} - 2\theta^T f_{i,j} + \theta^T Q_{i,j} \theta$$

where θ is a column vector obtained by concatenating either the columns of $\begin{pmatrix} B_2 \\ D_{12} \\ D_{22} \end{pmatrix}$ or the transpose of rows of $\left(C_2 D_{21} D_{22}\right)$.

The final expression is a quadratic criterion $c - 2\theta f + \theta^T Q \theta$ with $c = \sum_i \sum_j c_{i,j}(\omega_{j+1} - \omega_j)$, $f = \sum_i \sum_j f_{i,j}(\omega_{j+1} - \omega_j)$ and $Q = \sum_i \sum_j Q_{i,j}(\omega_{j+1} - \omega_j)$.

There is an analytical minimum at $\theta = Q^\bullet f$ ($\bullet$ is the Moore-Penrose pseudo inverse), which makes each loop of the biconvex optimization very fast.

Industrial application

As already mentioned in a paragraph above, this application illustrates the previously presented method of LFT modeling from a set of numerical models corresponding to a set of flight points and mass cases. These models are aircraft LFT longitudinal and lateral flexibilities for control design.

Description of the model

The set of aircraft models $(G_i(s))_{i \in [1,N]}$ correspond to variations of the parameters $\delta = (OT \quad Ma \quad V_c)$, being respectively the outer tanks filling rate, Mach number and conventional airspeed.

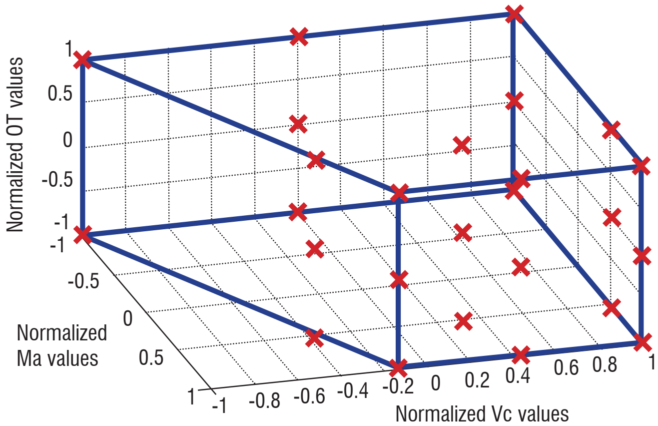


Figure 6 – Parametric domain of LFT model representativity . x : reference points for LFT modeling; - : parametric domain

These parameters vary inside the domain depicted in figure 6. For interpolation, $N = 27$ points are chosen inside this parametric domain.

The inputs of the model are the elevator δq and the ailerons in symmetric mode $\delta p_{sym} = \delta p_{left} + \delta p_{right}$.

The considered outputs are wing root bending load WRMX and wing root twisting load WRMY.

LFT construction

The LFT is then built according to the method presented in section 3.1, 3.2.1 and 3.2.2. The polynomial terms used for interpolation are computed by expanding the polynomial $(1+OT)^2(1+Ma)^2(1+Vc)^2$. This parameterization is sufficiently rich to obtain a very accurate interpolation. The obtained LFT has the following Δ-block:

$$\Delta = diag\left(\overline{OT} \times [\![_{42}, \overline{Ma} \times [\![_{30}, \overline{V_c} \times [\![_{52}\right)$$

$$dim(\Delta) = 110$$

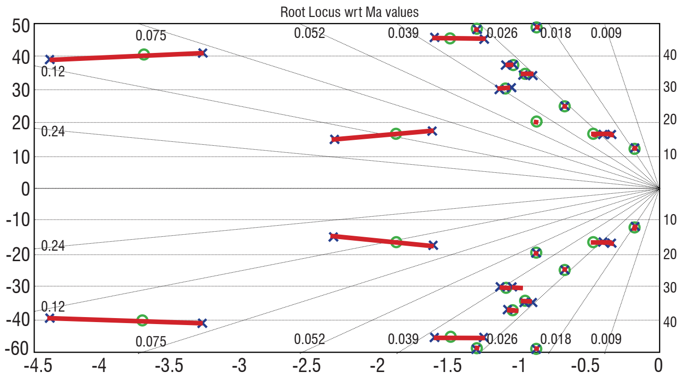


Figure 7 – Modal trajectories with respect to OT parameter variation
x: reference models modes; o: central model modes

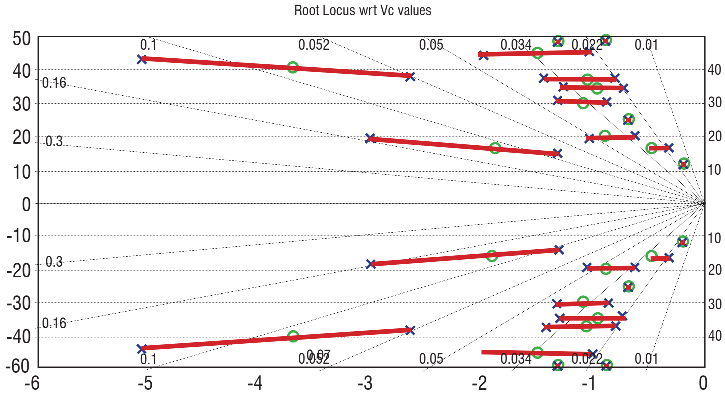


Figure 8 – Modal trajectories with respect to Vc parameter variation

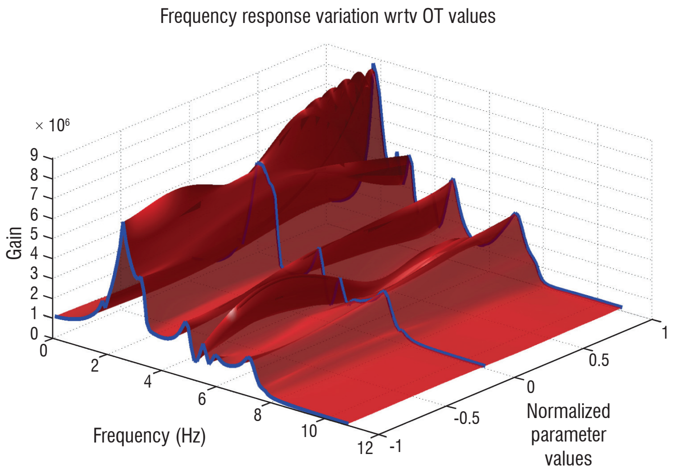


Figure 9 – Frequency response continuum with respect to Ma parameter
Solid lines: reference model's frequency responses

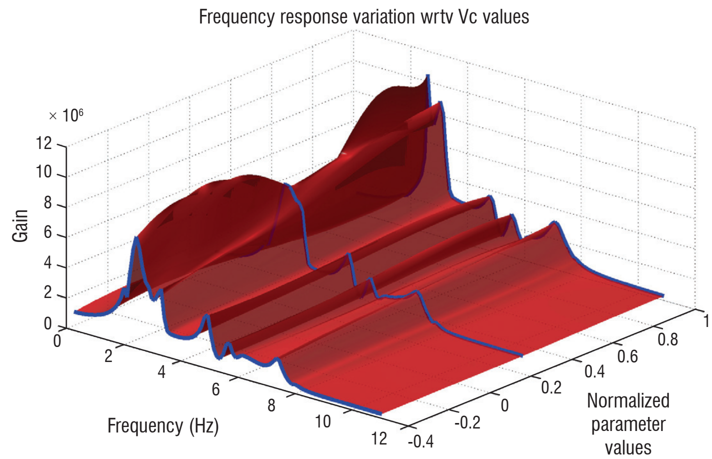


Figure 10 – Frequency response continuum with respect to Vc parameter
Solid lines: reference model's frequency responses

Validation of the LFT

The values of the validation criteria (5), (6) and (7) for the example are shown in table 1.

ε_{modal} %	$\varepsilon_{H\infty}$ %	ε_{H_2} %
1.27×10^{-5}	1.5×10^{-3}	9.28×10^{-4}

Table 1 – LFT Validation

Regularity check-up

Since an LFT is a continuum of models, the previously built LFT has also to be checked-up between the flight points used to design it. It must be proven that the continuum of modes (*i.e.* modal trajectories when δ varies) and the frequency response continuum are both regular. No "overshoot" must be observed, and ideally the continuum should vary linearly between two reference flight points.

In the application, the main directions of the parametric domain are explored to assess the regularity properties of the LFT.

The modal trajectories (see figure 7 and figure 8) show that the LFT has no unexpected behavior (*i.e.* no irregularities) in terms of modes. Besides, this proves the interest of the characteristic polynomial coefficients for A matrix interpolability. The frequency response continuum (figure 9 and figure 10) is fully satisfactory as well.

Conclusion

The method presented in this paper is used to design an LFT from a set of large-scale aeroelastic dynamical models. It is definitely adapted to complex and prominently numerical models, with no parametric structure knowledge whatsoever.

Naturally the least squares algorithm is used to interpolate the models with a basis of polynomials. Before interpolation, two steps are fateful in the process: the consistent reduction of the models and their state representations' transformation in a regularized companion state basis. In this way, the reduced models are made interpolable. After the LFT is created using the generalized Morton's method, its Input / Output accuracy can be optimized with an efficient biconvex optimization of the LFT state matrices. This algorithm was applied to both longitudinal and lateral aeroelastic models; the results showed very satisfactory modal trajectories and variations in frequency responses with about 20 states in both cases. This study, based on industrial complex aeroelastic models, clearly emphasized the efficiency of the tools provided by Onera.

These LFT models are well-adapted to full flight domain flexible aircraft control design. So these flexible LFT models are being used in the framework of research on the promising multi-objective flexible aircraft control extended to the full flight domain case [22] ■

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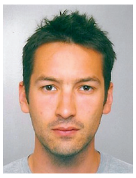
Acronyms

MIMO (Multiple Input Multiple Output)
SISO (Single Input Single Output)
LPV (Linear Parameter Varying)
LTI (Linear Time Invariant)
LMI (Linear Matrix Inequality)
MPC (Model Predictive Control)
ODE(s) (Ordinary Differential Equation(s))
PDE(s) (Partial Differential Equation(s))
$\bar{\sigma}(G)$ (Highest singular value)
iff. (if and only if)
resp. (respectively)



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Perception for UAV: Vision-Based Navigation and Environment Modeling

Nowadays, cameras and other exteroceptive sensors are on board of a large variety of automatic platforms, such as Unmanned Aerial Vehicles (UAV), space exploration probes and missiles. However, apart from this latter application, they are mostly used as payload and not to pilot the vehicle itself. In this paper, we focus on the use of computer vision for UAV perception to navigate through the environment and model it. This function is typically needed at low altitude in unknown or GPS-denied conditions. The measurements from exteroceptive sensors can then be processed to obtain information about the motion of the UAV, or the 3D structure of the environment. Our contribution is presented starting with the vision-based closed control loop, where image-based navigation is integrated to UAV control. Then, we focus on proper motion estimation techniques, like mapless relative terrain navigation or map-based GPS alternatives. Eventually, environment mapping solutions are proposed. In most cases, real image sequences coming from an aircraft or a hand-held sensor are used for validation. Our research underlines the need for new co-designed 3D sensors and massively-parallel computation technologies to go further in vision-based UAV navigation.

Introduction

Unmanned Aerial Vehicles (UAV) are mostly employed for observation or military intelligence missions. When they are not remotely operated, UAVs can only perform automatic functions such as waypoint-following, landing and take-off. For this purpose, they are equipped with high-grade inertial, GPS or radio navigation sensors. However, their navigation abilities constrain them to medium or high-altitude flight trajectories, far from any ground obstacle. The threat of an aerial collision is dealt with thanks to traffic collision avoidance systems and airspace segregation.

To extend the scope of operation of these vehicles, their safe navigation through an unknown environment or despite an intermittent or lacking GPS signal must be assured. To achieve this objective, UAVs must be equipped with exteroceptive sensors, efficient on-board computers, innovative estimation algorithms and new control laws to achieve a perception function.

In order to provide reliable information, the sensor measurements must be processed to deal with the coupling between the motion of the vehicle and the structure of the surrounding environment. Perception is also challenging because of the dependence of the measurement quality on the scene content, especially in the case of passive sensors. For instance, camera-based navigation is impossible over scenes with uniform texture, since the inference of geometrical information requires image feature association. Perception algorithms must also be robust to recurrent outlier measurements from low-level image processing, like optical flow or feature matching. Last but not least, passive sensors supply no direct information about the 3D structure of the environment, contrary to active ones like lidars, time-of-flight cameras, or Microsoft Kinect-like sensors. They must then be able to recover the 3D structure of the world with 2D-only image measurements.

Computer vision for UAVs is also challenging because of the vehicle itself. The first issue consists in the room available on board of commonly-considered platforms, such as multi-rotor or other aerial vehicles with Vertical Take-Off and Landing (VTOL) capabilities. Computers and sensors need to be placed in this very limited space, respecting weight constraints from some hundreds of grams to a few kilograms, usually no more than 2 kg [1][5][11][35][59]. Online flight computational capabilities have a direct influence on the UAV navigation performance since, contrary to a ground robot which can stop to wait computation results, a UAV is still in motion and even in hovering flight it needs to be stabilized. With its significant maneuverability and complex dynamics, it also entails a higher computational rate, which can be obtained through an Inertial Measurement Unit (IMU) aid for image processing. In practice, it is common to see solutions combining on-board computation and calculation deported to a ground station with the main drawback of having to maintain the data link between these and the UAV [1][5]. With progress in processor architecture, however, some teams have demonstrated some computationally greedy real-time algorithms, such as Simultaneous Localization and Mapping (SLAM) or stereo-vision as in [35][59].

In practice, the misreading of the 3D environment structure is usually the most penalizing. Three strategies are possible. The easiest involves installing an active sensor on board, such as a Microsoft Kinect [46] or a flash lidar [1][5][59]. On bigger systems [19][77], lidars can be mounted on a scanning platform to offer a higher field of view. In all cases, there is a price to pay in terms of greater electric power consumption and less room available for payload instruments. The second strategy is to use a stereo rig. 3D can be inferred from it, using an algorithm running on a CPU [35] or an FPGA board [3]. The use of a Structure from Motion (SfM) algorithm with a monocular passive camera is also possible, but needs an external aid to solve for the scale [90][91]. The third and last strategy simply consists in ignoring the 3D structure of the environment. In our point of view, there is a clear separation between the techniques involved in considering or ignoring this 3D structure. The former are usually common in the navigation literature, while the latter are often seen at the control and guidance level. We must distinguish the techniques assuming a planar world, like visual servoing [20][21][70][71], from the techniques using a specific video sensor to compute the image scrolling at high rate under certain assumptions about the structure of the environment. In all cases, these techniques exploit a limited visual information, mainly the image transformation between two views, to emulate some complex behavior, such as flying down the center of a canyon [41], terrain-following [37], landing [36][81], or obstacle avoidance [11].

This article outlines recent research work at Onera regarding the perception functions for UAVs and is divided into four parts. The first one focuses on vision-based control and guidance applications. At this level, image processing and command are closely related. Image processing is designed to provide limited 2D information but at high frequency, for example, an estimation of the image motion. These techniques are illustrated through two purposes: safe landing and the rallying/stabilization of a VTOL UAV to a reference position defined by an image taken at this position.

The second part tackles the problem of UAV self-localization and 3D environment modeling relative to a local reference frame. Here, computer vision is involved in the navigation task and must infer 3D information from an image sequence. These methods are complementary to those presented in the first section. They are typically used for the flight of small UAV, indoors or outdoors, when the GPS signal is blocked or jammed. They are designed to work at video rate for several seconds, between two map position fixes. The previously described techniques are prone to trajectory estimation drift by the accumulation of small motion estimation errors.

The third part addresses computer vision techniques to provide map-based correction information similar to a GPS. The idea is to register the current sensor output with a prior map of the environment tied to a global frame. Data association between the map and the current view allows the pose of the camera to be computed and consequently the position and attitude of the vehicle. In an ideal visual navigation filter, such a function operates at a low rate, combined with a relative motion estimator working at video rate. Figure 1 illustrates our vision of a vision-aided control and navigation system and shows how the different techniques described in the article could be articulated with each other. In the last part, we focus on environment mapping techniques, which is indirectly linked to the UAV navigation.

We present an offline mapping method for environment modeling that can be used for pre-flight mission planning and for the absolute relocalization task. A second subpart is dedicated to online obstacles.

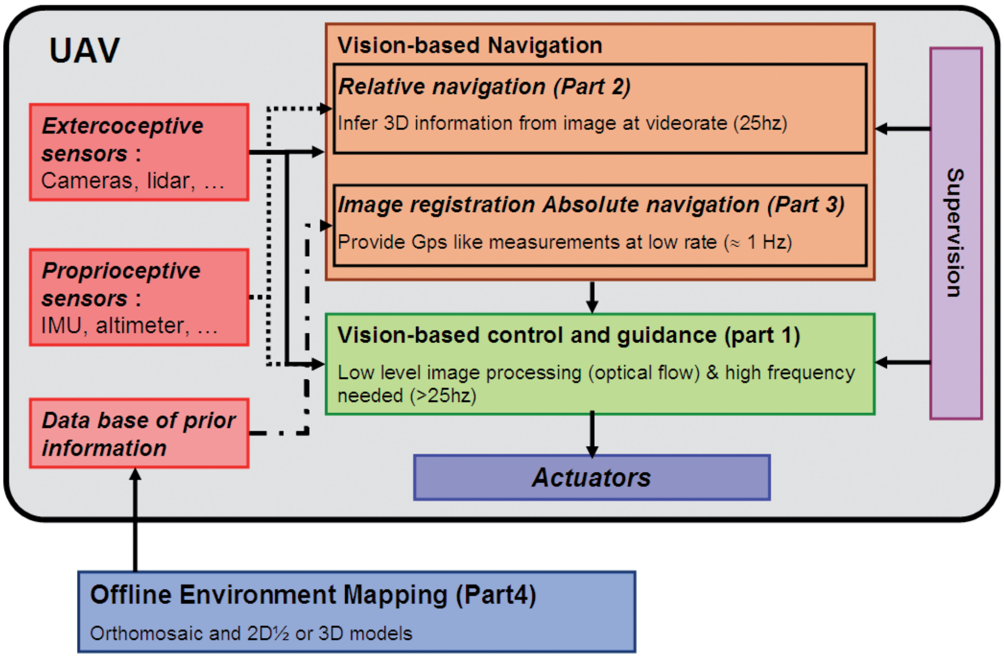


Figure 1 - Organization of a vision-based navigation and control system. Each block is related to a section of this article.

Box 1 - Optical flow

Optical flow (OF) is the field of apparent motion observed in the image plane during a video sequence. The «intensity conservation assumption», states that the visible difference between adjacent frames can be explained by «apparent motion» of pixels (or patches) from one image position to another. Actually, many image variations cannot be explained by such motion, for instance, motion blur, specular reflections, variations of illumination due to automatic gain tuning, occlusions, etc. However, one usually considers that these perturbations can either be corrected beforehand (illumination effects), or are rare (reflections, occlusions). Under the intensity conservation assumption, the optical flow derives from three contributors: the egomotion of the camera, the 3D rigid structure of the observed scene and the motion of moving objects that are in the field of view.
Figure B1-01 shows a residual optical flow norm map after global registration by a homography. Structure 3D and moving objects are very distinguishable. Optical flow then appears as a useful clue for autonomous behavior, and, indeed, it is used by most animals – including humans, of course. Its use in robotic application amounts to solving two coupled problems: (1) optical flow estimation (2) optical flow interpretation, in terms of the three components listed earlier (egomotion, 3D structure and moving parts).

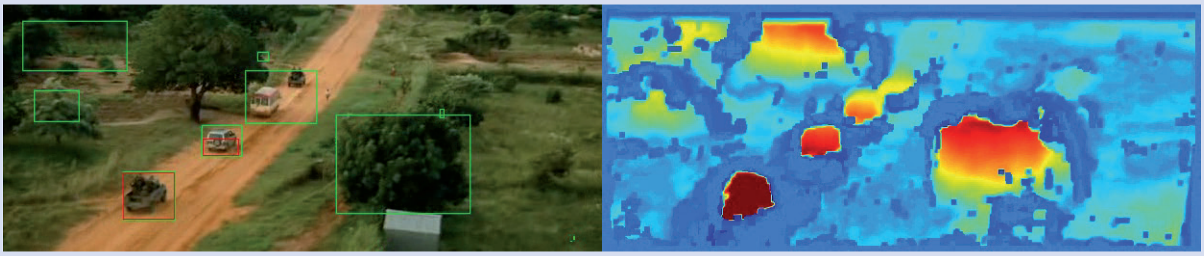


Figure B1-01 - OF norm after homographic global motion compensation. On the left, an image from the «Blood Diamond» movie. On the right, a compensated OF norm map. 3D structures and moving objects are easily detected.

Let us first comment about OF estimation. Dense OF estimation (where each pixel goes from t to $t+1$?), is an under-determinate inverse problem, which can be solved by spatial regularization. Several approaches have been proposed, ranging from costly global estimates with discontinuity-preserving properties [38][47][92] to very fast local estimates [48][54]. The latter can be obtained at video rate on full HD (2MPixels) images, thanks to FOLKIGPU [72], as illustrated in figure B1-02.

On the other hand, several applications, such as vision-based navigation, can be done with a sparse OF estimation, i.e., the estimation of the motion of a few hundred points spread over the image support – as for instance in all of the vision-based control problems of the section. Each point is chosen in a textured area, for instance using Harris-like detectors [34], and its motion is estimated by block matching techniques, often using cross-correlation maximization. These independent estimations are often improved by fitting a parametric global motion model (such as the planar homography model in the section "Online obstacle mapping for safe landing planning") with robust techniques – in order to discard wrong matches and other outliers. This robust parametric approach is very efficient in aerial imagery, where the assumption of a planar scene is often correct above a given altitude and over a large part of the field of view.

The last issue is the interpretation of OF so as to produce quantities that are relevant for the application at hand, be it control, obstacle avoidance or target detection. Let us first consider the case of a static environment and discuss of the coupling between the scene structure and the egomotion. In the late 80s, the following first order optical development was proposed by several researchers [52][56]:

$$\begin{cases} u = f\Omega_2 - \Omega_3 y + \Omega_2 x^2/f - \Omega_1 xy/f + f\,T_1/Z - x\,T_3/Z \\ v = -f\Omega_1 + \Omega_3 x + \Omega_2 xy/f - \Omega_1 y^2/f + f\,T_2/Z - y\,T_3/Z \end{cases} \qquad \text{(OF1)}$$

The left-hand sides are OF components (u,v) at pixel (x,y). In the right-hand sides, the focal length f, the translational and rotational components of the ego-motion (T and Ω) and the depth Z of the scene point whose image is projected at pixel (x,y) appears – in a referential fixed to the camera's center. Several remarks can be made regarding these equations. First, there is a decoupling between translational and rotational effects, with the depth appearing only in the translational terms. There are two kinds of constant terms, arising either from rotation components (O1, O2) or frontoparallel translation components T_1, T_2: with a limited field of view these terms can become indistinguishable. The rotational part (three first term) is independent of the depth: it can be estimated by analytical methods, see [39][40]. Then the translational part is an affine motion model scaled by the inverse depth: the center of this model is the «focus of expansion» FOE $(fT_1/T_3, fT_2/T_3)$. An example of such a motion model can be seen in figure 21, in the case of a (mainly) translational forward motion in a canyon. The scaling by the scene structure is clearly visible in the OF norm, opening the way toward 3D reconstruction from OF estimation. Around the FOE, the OF collapses. As a general result, the use of the OF for structure and motion estimation is best done «on the sides», i.e., as far away from the FOE as the orientation of the camera and field of view allow.

Lastly, let us comment on moving object detection and characterization using the OF. In aerial imagery, as already mentioned, the scene can often be approximated by a plane and (OF1) reduced to a second order polynomial model, which can be estimated and compensated. Residual motion can then be used to detect moving objects. This is done for instance in figure B1-02. In the case of low altitude flight over a 3D area, structure effects become important and detection should integrate clues other than OF, for instance learned knowledge on the appearance of the objects that are sought.

Figure B1-02 - Optical flow on a video from the BBC movie “One day on earth”. The colormap used here (source: Middlebury Optical Flow challenge [6]) at the same time codes the norm of the optical flow and the direction. This map is overlappable to the image on the right. We can easily detect the depth discontinuities.

Vision-based closed control loop

While the navigation task requires an estimation of the vehicle position and attitude, it has already been shown that coupling the output from exteroceptive sensors with a suitable control law enables automatic vehicles to achieve a complex and safe behavior, such as landing, terrain-following, flying down the center of a canyon or obstacle avoidance. We present here some work using 2D visual motion estimations and IMU measurements. First of all, we show how optical flow can be used to safely land an UAV. After that, two UAV stabilization techniques, related to visual servoing and based on the homography matrix computed between a reference view and the UAV current view, are explained.

Note, that, in both cases, a “target” must be pointed out in the image. The designation could be delivered by a human operator or by an “intelligent” embedded system.

Optical flow based control

In this section we present the control laws of a VTOL (Vertical Take-Off and Landing) UAV using optical flow as an input. A control objective is to land on a target while avoiding obstacles on its way. We first present the concept of optical flow and then describe the control laws that allow a UAV to achieve this objective.

Optical flow

Box 1 provides a detailed overview of optical flow, assuming the true image plane. For control tasks, it is more common to consider a camera as a spherical sensor, because of its passivity-like properties [32] knowing that it is possible to convert the plane image model to the spherical one [86].

Let P denote the coordinates of a point of the environment expressed in the camera-fixed frame, $\Re_D, p$ its projection on a spherical image and $\dot{p}$ its kinematics.
Then, the optical flow on a spherical image can be obtained by integrating $\dot{p}$ over a small image section W^2:

$$\phi = \iint_{W^2} \dot{p} dp$$

where W^2 is a hemisphere of the image on which we calculate the optical flow. Detailed derivation of this equation can be found in [33].

Landing on a target

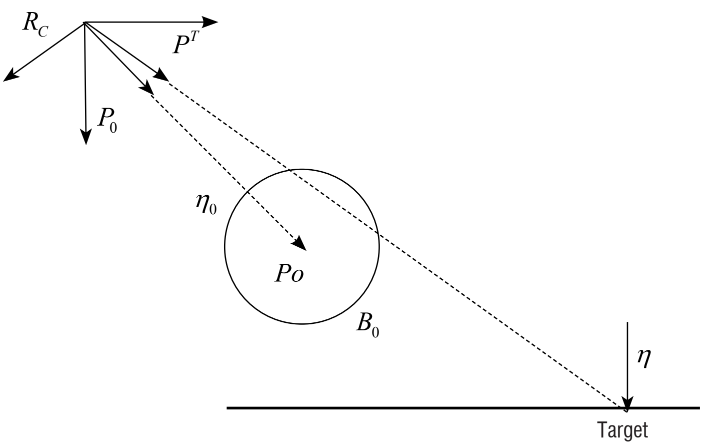


Figure 2 - Obstacle avoidance configuration

We can extract from the optical flow ϕ the translational optical flow, which is in fact the velocity relative to the ground:

$$\mathrm{w} = -\frac{\mathrm{v}}{\mathrm{d}} = f(\phi)$$

where v is the UAV velocity expressed in the inertial frame. The control law for landing is designed as a PI controller, by feeding back w and the position of the target in the image. This controller allows the target to be placed in the center of the image and to descend to land.

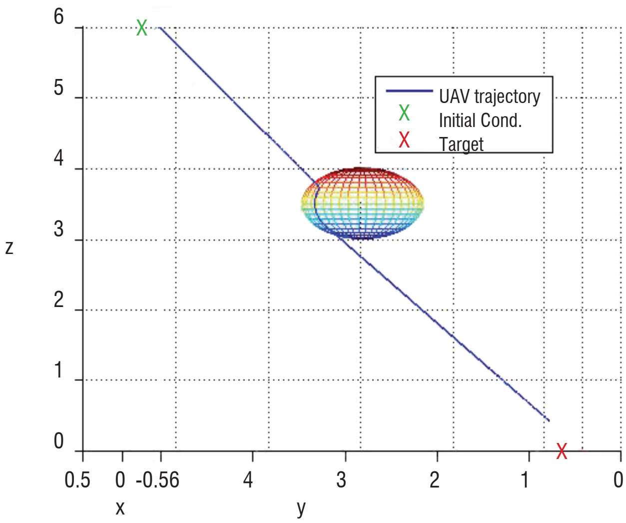


Figure 3 - Obstacle avoidance and landing. The obstacle is represented here by the repulsive sphere and we show that the UAV trajectory lays on the sphere surface

Obstacle avoidance

If the UAV crosses the repulsion sphere of an obstacle Bo during landing (figure 2), a repulsive term is activated in the control law. This repulsive part is a function of the integral of $d_o / d_o = \eta_o^t \mathrm{R}^t w_o$, which is a function of the translational optical flow of the obstacle. Choosing the repulsive gain correctly, we can guarantee that the UAV avoids the obstacle. Figure 3 shows simulation results of UAV landing trajectories, with and without obstacle.

Inner-loop vision based control for UAV stabilization

The previous parts show the benefit of an onboard video camera on the guidance/ navigation functions of a UAV. Confronted with the weaknesses of other sensors (GPS jamming, need for external devices, etc.), they also question the possibility of a UAV control system relying on a very minimal sensor suite, namely only on visual information and on other on-board sensors (typically gyrometers to measure angular velocity).

This problem is highly challenging for several reasons, some of which are related to image processing: the richness of visual information, which questions the associated computational burden, and the need for real-time computations or the required robustness to changing light conditions.

Furthermore, vision based control is also highly challenging from an automatic control prospective: depth information acts as a gain in the control loops and it cannot be extracted from images without extra knowledge; velocity is not measured; the UAV orientation is unknown unless, again, extra assumptions are made; the relationships between point coordinates seen from a camera are nonlinear, and so are helicopter dynamics, thus calling for nonlinear control techniques when addressing stability in a large flight domain. Finally, several types of UAV, such as helicopters, are not fully actuated, thus increasing the control task difficulty.

For these reasons, vision-based control for UAVs has been mostly addressed in the past years by the use of restrictive assumptions. First of all, the huge majority of works consider the observed landmarks to be lying on a plane, this assumption being necessary to use the homography matrix. Moreover, most works assume that the position and orientation (the «pose») of the UAV can be extracted from the images, leading to a more standard UAV control problem [57], or that enough knowledge is available for the dynamics to be able to be somehow inverted [31]. Several works do not consider the dynamics of the UAV (or that of another system), such as [23]. This happens for instance when the system is supposed to be fully actuated (in [13], a quadrotor is considered, where the dynamic can also be considered to be actuated).

A few recent works have addressed the nonlinearities of the UAV and camera models, often leading to local stability results [33] (the UAV has been proven to be stabilized, as long as it does not start too far off from the desired pose). Some of these works also prefer to use a spherical image camera – as mentioned in the previous part of this article dealing with optical flow – because of their passivity property, which helps in the control design steps [13].

Finally, in some recent approaches, the assumption of the knowledge of the normal to the target is made in the camera frame [50], leading to interesting but still restrictive results.

In this context, we have built on these previous works, in order to reduce the need for such assumptions still further, and have proposed two control laws:

- in the first one, a linear control law uses the homography matrix to avoid extra assumption;
- the second control law is a nonlinear control law, with an almost global stability domain.

The task at hand is to stabilize a UAV helicopter flying in front of a planar object, on which points of interest (Harris, Fast, etc.) can be extracted. The control task is to make the current image equal a reference image, supposedly taken by the UAV from the desired pose. The object nature and size, current or reference distance to object, velocity, position or orientation of the UAV are all unknown; we only have the current and reference images, as well as the gyrometer angular velocity measurements.

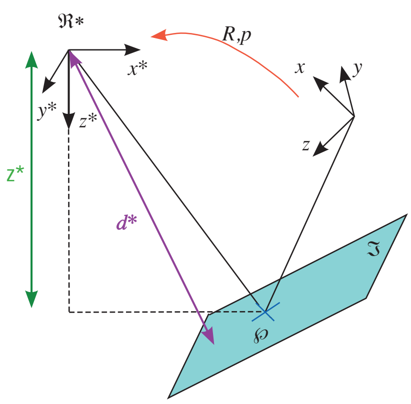


Figure 4: planar target object seen from two viewpoints

The linear control law [70]

The first important question is: how can relevant information be extracted from the images taken by the video camera? If the observed scene is a planar object seen from two viewpoints, one can estimate the so-called homography matrix, which is the transformation between the coordinates of any point of the target plane, as seen from the two viewpoints; it encompasses the rotational and translational information, while it is not possible without assumption to extract these two elements:

$$H = R^t - \frac{1}{d^*} R^t p n^{*t}$$

where R is the rotation matrix between the two viewpoints, d^* is the distance to the target plane from the reference position, p is the translation between the two viewpoints, and n^* is the normal to the target plane (see figure 4). All of these quantities are unknown in the considered scenario, so that we are left with one global measurement, which implicitly encompasses position/orientation information.
We have chosen this matrix as the core measurement for the control task: based on [9], we have defined a new error vector according to:

$$e = \begin{bmatrix} e_p \\ e_\theta \end{bmatrix} \text{ with } e_p = (I - H)m^*,\ e_\theta = vex\left(H^T - H\right) \text{ and}$$

$$vex(x) \text{ defined by : } \forall x \in \Re^3 \ : vex\left(SkewMatrix(x)\right) = x$$

$$\overline{e} = Me \text{ where } M = \begin{pmatrix} 2I & S(m^*) \\ -S(m^*) & I \end{pmatrix} \text{ and } m^* = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}$$

In these equations, the first error vector e was defined in [9] so that it is bijectively related to the position/ orientation information. The goal of our proposed error vector $\overline{e}$ is to recover vectors that are closer to the position/ orientation information, so that a control law close to standard linear control for helicopters can be applied. In this framework, m^* is a pointing direction in the reference camera frame, which is chosen equal to the camera axis (third component of the basis). With these definitions and this choice for m^*, one shows that rendering this vector null ensures that the UAV is at the desired pose. Moreover, based on this vector, a nested loop linear control law was defined, with the addition of a dynamics augmentation. This control law is shown to stabilize the UAV without velocity measurements and without extra knowledge about the scene (size, distance, etc.) for a very wide range of values of the unknown distance to target: as long as rough bounds on this distance are known, the UAV can be stabilized. Finally, a heuristics for gain tuning was provided to fine tune the UAV performance.

The nonlinear control law [71]

Building on this first linear result, a nonlinear control law was designed. The procedure adopted was similar to that adopted in the linear case: to define an error vector recovering information close to position/orientation, then use this vector in a framework inspired by more standard helicopter UAV control. The previously-defined error vectors, although well-suited for the linear context, were not suitable for the nonlinear domain. We have defined new error vectors, once more computed from the homography matrix:

$$\pi = He_2 \wedge He_3 - He_1$$
$$\gamma = gHe_3$$

In this definition, π can be shown to be close to the position error information, whereas γ is close to the orientation error information. With these new error vectors, the error dynamics, although described with the use of unknown parameters (reference distance to target, normal vector to the target plane) and unmeasured variables (velocity), are rewritten in a form closer to a standard UAV dynamics model, which permits recent results to be used in the field of nonlinear control for helicopter UAVs [42][43]. The general form of the dynamic equations was considered, in order to prove a general result on the nonlinear robust control of an uncertain dynamic model, with the use of saturation functions. This result was applied to the vision-based control, with the aforementioned error vector, in the case of a vertical target plane. This assumption does not mean that the target plane orientation is fully known; in more recent and yet unpublished work, this assumption is forgotten. In this context, the system with such a nonlinear control law was shown to be stable for almost all initial conditions.

Future directions include the introduction of this control law into a guidance framework, which could lead to following a trajectory relying solely on video camera and gyrometer sensing.

Vision-based relative navigation

Techniques presented in the previous part exploit image measurements for guidance and control tasks. This involves a close interleaving between image processing and flight control software, because the vehicle state is not explicitly recovered by vision.

In contrast, the navigation system recovers at each time (as a minimum) the position and attitude of the vehicle. In addition, it must be able of take into account new information about the vehicle environment, for example to avoid an unknown obstacle. Here we consider the case of relative navigation, defined as navigation without a system able to locate the vehicle in an external reference frame, such as the GPS or a terrain correlator. In relative navigation, the reference frame is commonly the sensor frame at the beginning of the mission or the last available GPS statement.

The methods described here extract 3D information about the camera/ vehicle motion and the environment from a vision sensor, eventually helped by inertial sensors. These operations rely on a geometrical model of sensors, as detailed in box 2.

The first subsection describes a system combining IMU and a downward looking camera for recovering the UAV state during a target tracking scenario. In a more general manner, the two following subsections talk about visual 3D motion estimation and its accumulation over time. The estimated state provided by such techniques can be exploited to build a representation of the local environment, as described in the last subsection.

Optical flow-aided inertial navigation for ground target tracking in an urban environment

This section focuses on developing a UAV navigation and guidance system for air-to-ground target search and tracking missions in an urban environment [89]. The monocular vision-based target localization and tracking problem has been well-studied, with various applications such as aerial refueling, formation flight and ground target

BOX 2 – Camera model and calibration

One camera provides oriented information: the radiometric or/and distance information at one pixel comes from a certain direction relative to the optical axis. In order to infer geometric information from images, the process of geometrical image forming must be mathematically explained.

The direct camera model describes the image position from the 3D feature position (relative to camera position). The pinhole model, the simplest camera model, corresponds to a central projection whose center corresponds to the camera focal point. Thanks to the projective theory, this model is formulated as a linear operator, described by a 3x3 upper-triangular matrix K, where f_u, f_v, u_0, v_0 correspond respectively to the horizontal focal distance, the vertical focal distance and the coordinates of the central point projected on the image plane.

$$K = \begin{bmatrix} f_u & 0 & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{bmatrix}$$

This model is well-suited for long-focal optics. By reducing the focal length, some geometrical distortion caused by the optics appears. To deal with it, Brown et al. [17][30] have proposed a modified model adding polynomial disturbance before the affine transform defined by the matrix K. Two sorts of distortions are identified: radial distortion, which is the majority and is described by 3 parameters, and tangential distortion, which is described by 2 parameters and describes the misalignment of the lenses w.r.t. the sensor plane. See the page "Description of the calibration parameters" on the J.Y. Bouguet Website [12].

In the case of a very large field of view, like fisheye lenses or catadioptic lenses, the Barreto [8] camera model is the best suited. This model adds 2 parameters to the previous ones.

Estimating these parameters is carried out during the calibration process. It consists of taking several images of a known geometrical pattern, like a checkerboard. Knowledge of the matching between image measurements and 3D measurements permits intrinsic parameters to be estimated thanks to a bundle adjustment process (see box 3). Some toolboxes are freely available on the Web, the most famous is due to J.Y. Bouguet [12].

For some exotic lenses, the single viewpoint condition is not respected and some authors propose to replace the parametric camera model with a look-up table pixel↔3D ray direction [73].

observation. However, most assume a UAV operation in an open space, but not in a congested area.

Two main challenges associated with an urban environment are: i) GPS signals can be degraded or even denied, and ii) there are obstacles to be avoided. Those two conditions are seldom incorporated in the UAV visual target tracking problem. Figure 5 summarizes the system that we propose to address those two issues, using onboard vision sensors. A classic monocular vision-based target localization and tracking system is augmented with optical flow-aided inertial navigation and the lidar-based obstacle mapping and avoidance algorithm.

For UAV flight safety during urban operation, it is critical to maintain its navigation capability in case of GPS signal loss. In order to limit divergence of the inertial-only navigation solution, we have suggested the use of optical flow measurement to compensate the UAV velocity information [88]. The navigation filter is based on the extended Kalman filtering method to simultaneously estimate 3D position and velocity of a target and those of the UAV. Figure 6 compares UAV trajectories estimated by the optical flow/inertial and the inertial-only navigation filters. They are calculated by using the inertial sensor measurements and the onboard camera images synchronically recorded during a UAV target tracking flight. The suggested system can provide a navigation performance equivalent to that of a GPS, while the inertial-only navigation solution diverges quickly. We are currently working on adding a ground altitude measurement with a laser for further improvement of the localization accuracy.

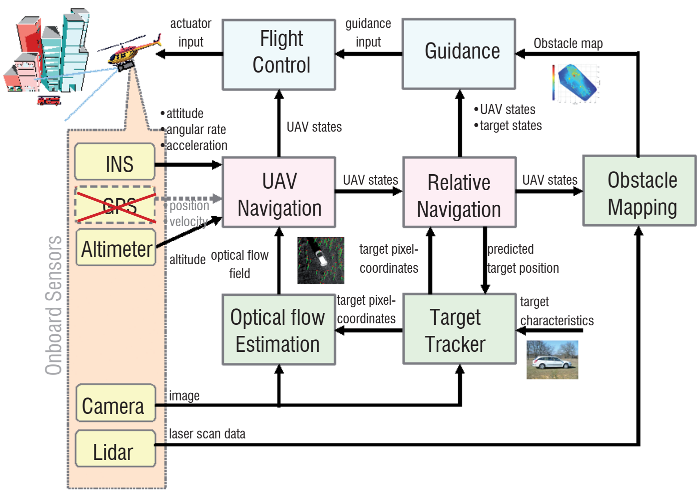


Figure 5 - Onboard navigation and guidance system for visual target tracking

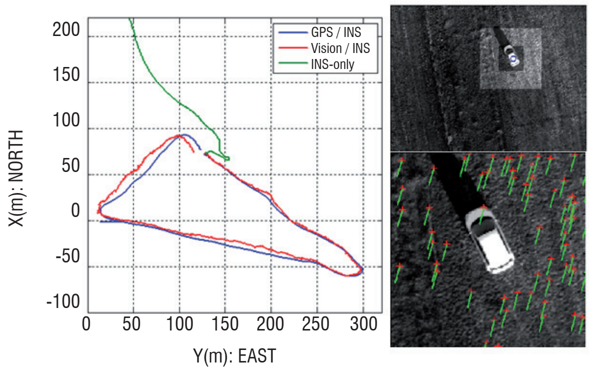


Figure 6 - Optical flow-aided simultaneous visual target tracking and navigation. The chart on the left compares three trajectories: in blue, the ground truth (from GPS/INS), in green the trajectory from inertial measurements only and in red the trajectory from our optical flow-aided navigation filter. On the right, an image with our target and optical flow.

Visual odometry

In the previous technique, the UAV state is partially recovered by vision, altitude and attitude being measured by dedicated sensors. In addition, a strong assumption was made about the environment. In contrast, visual odometry recovers the full relative motion parameters between two successive displacements in time, with the help of visual sensors. To achieve this objective, a visual odometer more commonly exploits 3D measurements from a stereorig or a depth camera. Indeed, under the commonly used hypothesis of stationary scene, the non-alignment of corresponding 3D measurements is only due to the sensor motion. Thus, recovering the sensor motion is equivalent to estimating the rigid 3D transform (rotation + translation), which aligns the two 3D measurements sets at best.

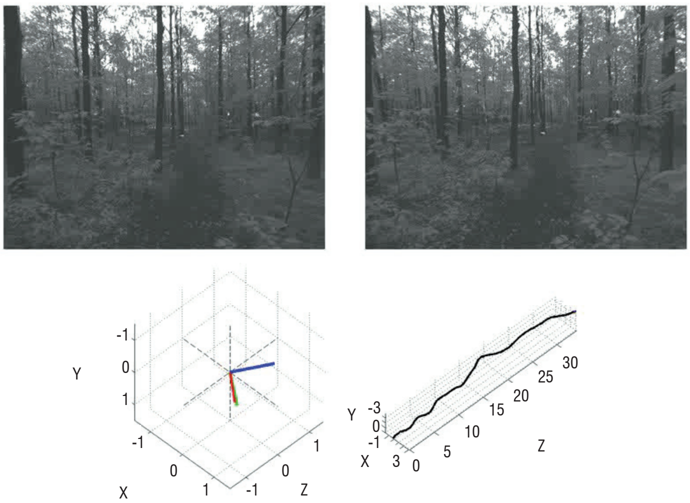


Figure 7 - Camera attitude and trajectory relative to the frame of the first image of the sequence with stereo visual odometry. On the top, one stereo image. On the bottom left, the current attitude in the reference frame; at right, the trajectory. No ground truth available, but the result is quite similar to our walk.

The most common visual odometer uses a stereorig and a sparse set of image features like Harris corners [34], FAST corners [74] or SIFT points [53]. Features, extracted from each stereo image, are matched in two ways: the stereo-matching gives the 3D localization of the feature by triangulation; the temporal matching supplies the matching between 3D measurements. From here, two strategies can be followed: the use of a 3D-3D pose computation algorithm [45] or a 2D-3D one [55]. The first minimizes a global distance expressed in the 3D Euclidean space; the second minimizes a distance on the image plane. Modern algorithms are robust to matching error through the RANSAC mechanism [29]. Figure 7 shows the result of a trajectory estimated by the real-time state-of-the-art Onera stereo visual odometer.

Stereo visual odometry can be applied on natural scenes (like in figure 7 and figure 8). In other cases – such as an indoor case, see figure 9 – a RGBD (Red Green Blue and Depth) sensor is a better choice because it can measure relative 3D information, despite the lack of texture. In [44], the authors proposed an algorithm that relies on a probabilistic framework, where a global matching criterion applied to extracted geometric features can be evaluated in parallel in the projective plane defined by the sensor camera. This algorithm benefits from a fast GPU-based implementation and has been successfully applied to Kinect data. Compared with local registration methods like the Iterative Closest Point (ICP, [10]), the proposed approach is natively robust to large camera motion (rotation or translation). The algorithm basically comprises two successive steps:

- First, sparse structures (3D contours corresponding to a list of edges) are extracted from the depth image and used in a pose score evaluation for different movement hypotheses;
- Then, a likelihood function is defined on the set of all possible transformations and used in the final decision process.

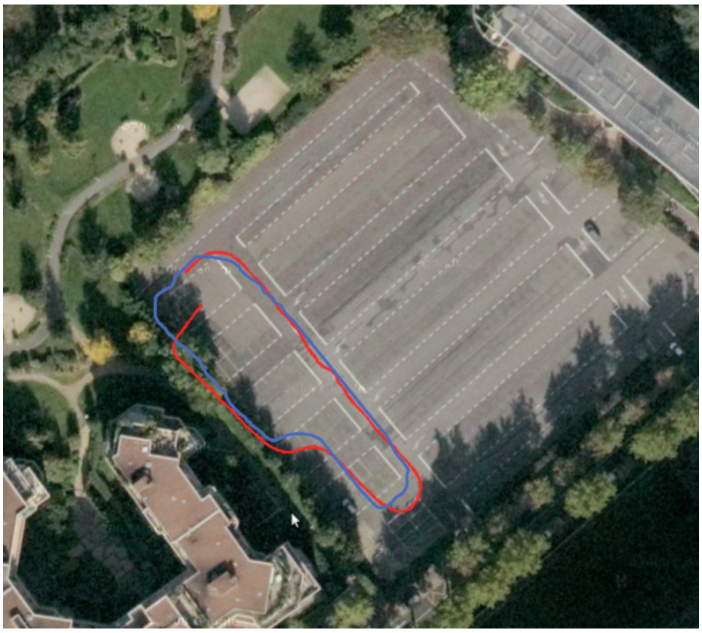


Figure 8 - Trajectory obtained by visual odometry (in red) is quite similar to the "ground truth" (blue). Note the drift: We have made a loop, but the ends of the path do not coincide.

Good results have been obtained on structured environment, as shown in figure 9. Here the transformation is selected to maximize the ML criterion. As we can see, in this case, the selected transformation permits the two point clouds to be precisely aligned. Future work will focus on coupling the pose estimation with a particle filtering approach and its embedding in a global and multi-scale SLAM framework.

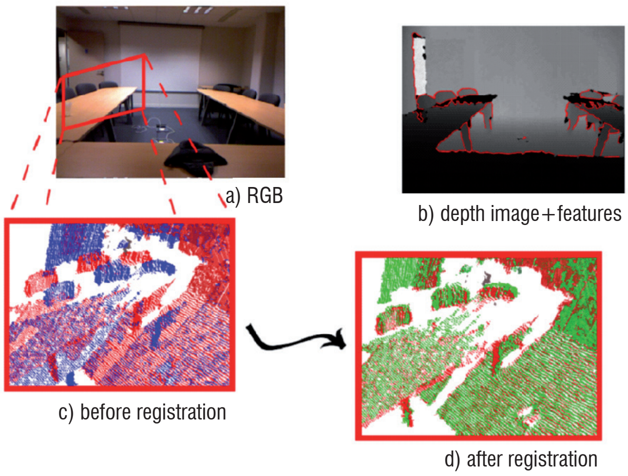


Figure 9 - Dense 3D point registration by the 3D features-based probabilistic pose developed by Onera [44]

Visual odometry is also addressed without 3D sensors like a simple monocular camera. The scale cannot be estimated directly from the sensor and external information is needed, such as an inertial measurement unit (IMU) or some known-size landmarks. We will cite Nistér et al. [64]which use the epipolar geometry and an efficient algebraic algorithm to compute the relative pose [63] and Caballero et al. [18] which use the decomposition of the homography matrix in the case of planar scenes.

vSLAM: Visual Simultaneous Localization And Mapping

A visual odometer gives the camera relative motion between two successive instants as output. The naive global trajectory estimation approach combines successive rigid transforms, accumulating unbounded estimation errors. The vSLAM algorithms attempt to reduce the drift by taking into account the geometric constraints between the sensor trajectory and some 3D landmarks tracked over time and forming a map – the Mapping term in the vSLAM acronym.

The main difficulty is due to the online nature of the algorithm: landmark positions and UAV trajectory must be refined continuously before the acquisition of the entire information. Ideally, a vSLAM algorithm must refine these parameters at each time from all of the previous algorithms, leading to an intractable formulation. In order to approximate this ideal solution, filters are designed to work on a short temporal window (from one to ten views). A great variety of filters are proposed in the SLAM literature: local bundle adjustment (see box 3) [62][78][79], Non-linear Kalman Filters (Extended, Unscented) [22] [24],or particle filter [60]. These filtering solutions have then been declined with different sensors (mono, stereo, RGBD) and with different kinds of features (point, segment, planes) and associated image processing.

Within the scope of initial work on online environment modeling, we address the problem of monocular vSLAM. We have implemented the EKF-vSLAM described in Davison [24] and Civera [22] seminal works. The state vector – containing firstly current position, attitude, linear and rotational speeds of the UAV and secondly a dynamically managed 3D landmark map– and the associated covariance matrix are updated sequentially in a prediction-measure-correction scheme. The 3D landmarks are parameterized in the inverse-depth manner [22] to simplify the non-delayed vSLAM process. With a front-mounted camera, image features and descriptors must be robust to scale and appearance changing. Unlike the original algorithm, our implementation uses DAISY descriptors [83] and we observed a better convergence on a UAV monocular image sequence, as depicted in figure 10.

Most of the previous techniques work at the standard video-rate (25-30 hz) and perhaps at a higher frame-rate (i.e., [76] announces 60 hz). Since EKF-based and Bundle Adjustment-based vSLAM need to invert a matrix whose size is related to the number of estimated parameters (viewing parameters and structure parameters), these performance are possible only by constraining the number of landmarks in the auto-generated map. In an EKF-vSLAM and standard matching techniques (i.e., without the DAISY descriptor), the video-rate is reachable with about 50 3D points in the map. This constraint prevents the use of vSLAM techniques in large environments. To bypass this limit, some techniques have propose the use of local maps regularly initialized and ordered in a graph of maps related by rigid geometrical transformation (translation, rotation) [66][68].

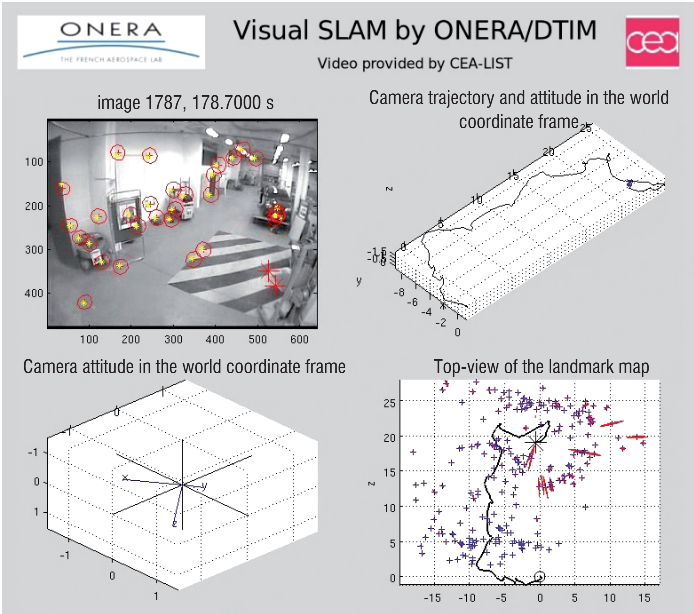


Figure 10 - DTIM EKF-vSLAM on an indoor UAV images sequence provided by the CEA-LIST

The map built by a vSLAM is not sufficient for navigation through obstacles or a congested area. In the next part, we address denser environment modeling techniques.

Online environment modeling

The data acquired by the exteroceptive sensors is also processed, in order to provide a digital model of the environment for the navigation and guidance algorithm. We describe the requirements for this model below.

Firstly, the considered application does not need a realistic and very accurate environment model – as used for view synthesis or virtual architecture. Indeed an exhaustive ternary classification of the 3D space as a free space (safe to navigate), obstacle area and unknown area is generally sufficient for planning a collision-free path. The second aspect concerns the modeling strategy. As UAV acquires progressively more knowledge about the environment, the function must be able to combine these fragments in a sequential way, as in the SLAM manner. Lastly, the model must offer fast access to the 3D information and must be as compact as possible, in order to deal with the constraints from the embedded system (memory and computational resources are limited) .

Three environment representations could be considered: i) 3D point cloud ii) 3D meshes iii) voxel-based space quantization. Despite the unbound memory footprint, voxels-based solutions are commonly used because they natively offer fast access to information content (by three indices) and a useful neighborhood relationship between these elements. The common solution consists in computing occupancy likelihood in a stochastic update way within a voxel-based technique [2][3][27][61][93].

Two interesting references deal with the main drawback of the voxel representation. In [3], the authors propose to combine a locally classical voxel array with a global simplification stage, consisting in occupied space by polygonal convex hull. [93] shows how an octree-based voxel representation could improve the occupied memory space, without prior knowledge about the global explored volume.

In recent work, we have evaluated the Octomap solution [93] with RGBD and stereo-rig data. Figure 11 shows the 3D model obtained from a depth map provided by a home-made stereovision algorithm. Typically, the Octomap processes our data (640x480 depth maps) at 1 to 2 Hz. 90% of the computation time consists in the ray-tracing operations used for updating occupancy likelihood in the voxel grid. We have integrated a pre-processing of the depth maps proposed by [1]. The idea is to identify in the depth maps pixels corresponding to 3D points belonging to the same voxel and to replace multiple ray traces by one only. Practically, we use multi-resolution depth maps. This technique is called the "pyramidal approach". Figure 12 shows some performance analysis results. The graph at the top compares the number of ray-tracings for different voxel resolutions with the pyramidal approach for a depth map sequence. The greater the voxel resolution, the greater the gain is. In this example, the gain in the coarsest resolution is of around100 w.r.t for the case without pyramidal approach. This result was expected. In order to more precisely qualify the impact factors, we put a lot of boxes in an office room and acquired depth maps during the tidying up (see the photo at the bottom left corner in figure 12), boxes being removed from the foreground to the background. For a same voxel resolution, the curve shows that gain also depends on the obstacles ↔ sensor distance.

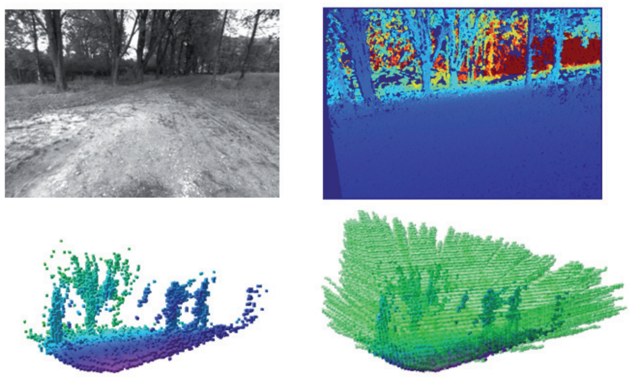
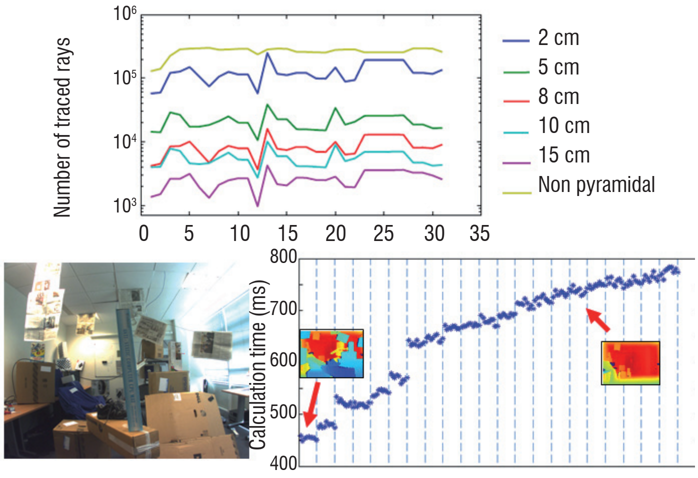


Figure 11 - Online environment modeling. From top to bottom, from left to right: grayscale stereorig image, depth map by stereovision, occupied voxels, free voxels in semi-transparent green. The obstacles within a radius of 10 meters are correctly modeled.



Tidying step: from the foreground to the background

Figure 12 - The gain obtained by pyramidal approach varies with voxel resolution (at top, in terms of traced rays) and the cluttering of the scene

Image registration for absolute navigation

Vision-based relative navigation techniques presented earlier analyze the image motion of feature points to estimate the current pose of the vehicle. Except when these features stay or come back into the field of view (within a vSLAM with loop-closure detection, for example), position and attitude estimation suffers from a drift due to an unbounded error accumulation, as illustrated in figure 8. This is an issue encountered, for example, by a UAV cruising outdoors, or by a spacecraft landing on another planet from an orbit trajectory. Here, we focus on two image processing techniques to recover the vehicle position and attitude relative to a global frame. They both rely on prior geo-referenced data. The first one is a dense technique: all of the image pixels are used. The second one is sparse and relies on image feature matching.

Registration of video to geo-referenced imagery

Accurate geo-registration of video captured from an airborne platform, such as a UAV, is required for image analysis. Most of the time, the recorded data (position, attitude, zoom) supplied with the video is not sufficiently accurate for military applications. To meet this requirement, we propose an approach to automatically register airborne video to geo-referenced imagery and digital elevation models. A few manually selected "key frames" are automatically registered to geo-referenced imagery, using Mutual Information optimization [87]. This step provides ground control points that will be used to feed the "Bundle Adjustment" procedure. The "Bundle Adjustment" (see box 3) estimates the viewing conditions (extrinsic and intrinsic parameters) of each image, using tracks of salient features generated over the sequence by the KLT tracker [80]. When the registration of a single frame is not possible because of a too narrow field of view of the video, a mosaic is built to enlarge the field of view, in order to enable registration through mutual information optimization.

Good estimates of intrinsic parameters are required to initialize the processing chain. When this is not the case, as in the videos we used, an optional "Auto-calibration" module may help to recover sufficiently accurate focal lengths to initialize the process. The auto-calibration procedure is based on the reference [82]. The figure 13 presents the general scheme of the proposed video geo-registration chain. Figure 14 shows a result after the automatic registration of a keyframe on the orthoimage.

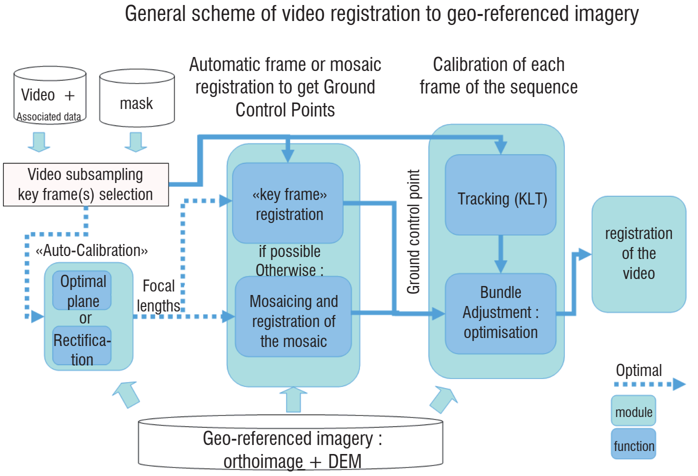


Figure 13 : Synthesis view / Flow chart of the video geo-registration method developed at Onera

A quite similar method was developed and applied to UAV navigation in [16]. In this reference, a correlation-based image registration is proposed. It differs from ours by the optimized parameters – a 2D translation versus a homography – and the maximized criterion – cross-correlation versus mutual information. Using this simplest registration model is possible, because the image registration module is combined in a complete navigation system with IMU measurements and a homography-based visual odometer, in order to adjust the UAV altitude and attitude.

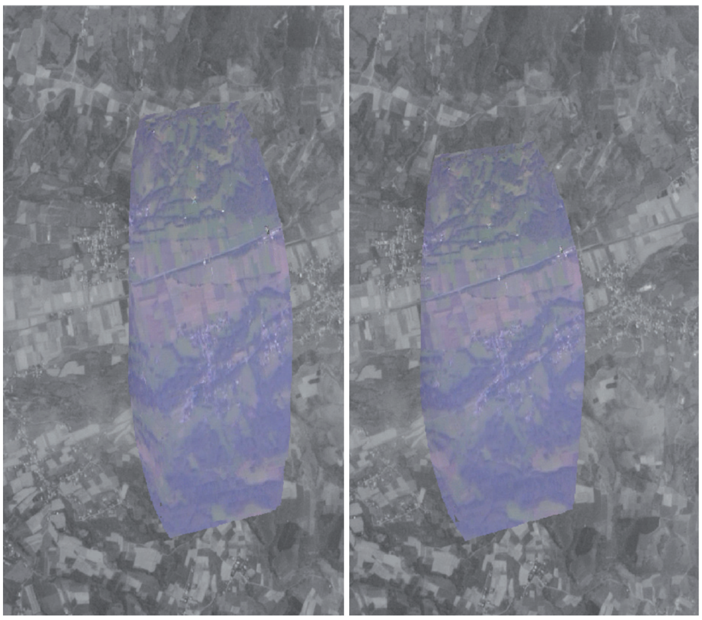


Figure 14 - Example of image registration on an orthoimage, by the alignment method based on the maximization of the mutual information. On the left, before processing. On the right, after processing, the fitting at the borders is great in most cases.

Feature-based registration for pinpoint planetary landing navigation

Pinpoint landing capability is required for several future planetary missions to the Moon and Mars. Since there are no GPS or radio beacons to provide position fixes on such planets, inertial-only systems that have been used up to date suffer from an error drift and cannot guarantee the required landing precision of 100 m. One way to reduce and maintain the navigation error low is to identify landmarks on the surface with terrain sensors.

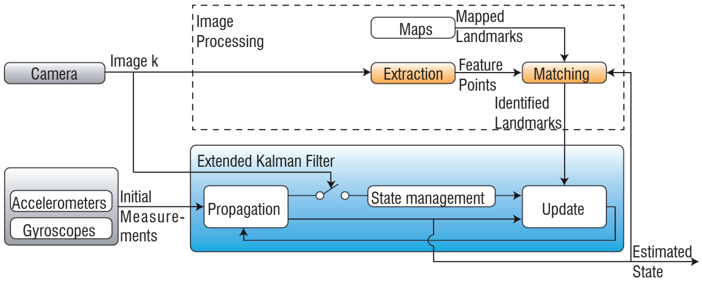


Figure 15 - Vision/Inertial fusion architecture for planetary landing

In [25], we proposed an absolute navigation algorithm that uses a simple optical camera to identify landmarks on a terrain map built from orbital data. These image-to-map matches are used as measurements in an extended Kalman filter, depicted in figure 15, which propagates inertial measurements to estimate the state in terms of position, speed, attitude and inertial biases. Inertial measurements allow high-frequency estimation to be achieved, to correct abrupt motion in the control loop. They also keep the navigation going when the camera is flown above a shadowed area, where no optical measurements are available. Vision measurements are processed at a lower rate, which is constrained by the on-board processing time of usually a few seconds. These delays are taken into account in the filter through a state management block, which adds the pose estimate of the camera at the time of image acquisition in the state of the filter and correlates it with the current estimate through the inertial measurements. Although compensated, this delay issue underlines the need for a computer-efficient visual landmark matching block, in terms of processing and memory requirements.

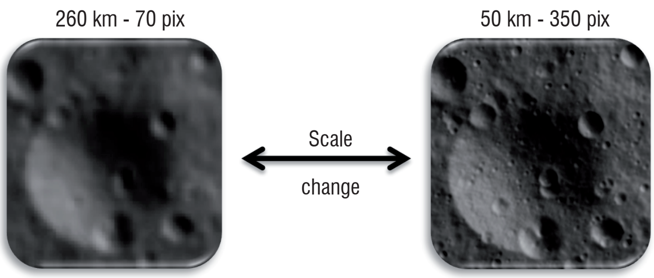
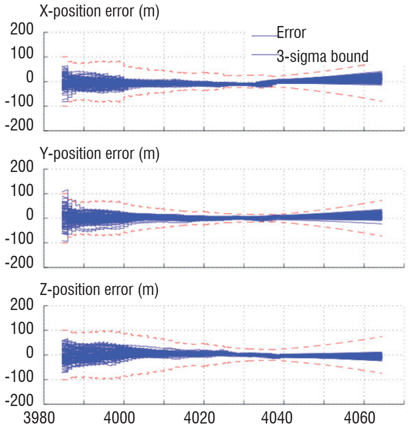


Figure 16 - Scale change illustration. The same crater is imaged by the same camera at 260 km of altitude (left) or 50 km (right)

There are three main challenges for the vision system to be used for planetary landing. The first is to be robust to illumination differences between the descent and the orbital image used to create the map. Geometric landmark descriptions, such as that proposed in [67], are more robust than radiometric ones in this respect. They are also a lot lighter in memory requirements. The second challenge is to be able to match features on descent images shot over a broad range of altitude, with landmarks selected from orbital images taken at a constant altitude. Altitude change converts into a scale change at the image level, which is illustrated in figure 16 and is equivalent to an image smoothing. Namely, one image usually shows many more details than the other one and this is an issue to be faced by the image feature extractor. Eventually, the third vision challenge is to make use of 3D information of the world but with a 2D image only. A flat world assumption is often made in vision systems to face this problem. However, this can no longer be assumed to land on very bumpy bodies such as asteroids, or at low altitude over uneven areas on the Moon or Mars.

The vision system proposed in [67] proposes a solution to tackle these challenges. It creates a map by selecting landmarks as Harris-Laplace features on an orbital image of the area [58]. Unlike craters, these features can be found on any image of a non-uniform surface, which makes them very generic. The 3D coordinates of these landmarks are derived by back-projecting their image position in a ray that intersects a DEM of the surface. The map is an Nx5 array made up of the 3 world coordinates of each landmark, their characteristic scale on the orbital image and their cornerness scores at this scale. Online during the descent, *a priori* state estimates from the filter are used to predict which landmarks will be seen by the camera and the a priori state covariance allows an image research ellipse to be defined for each of them. Not all landmarks are selected as matching candidates, however. Only those for which the research ellipse is not overlapped by another, or those that have the highest cornerness measure of all of the overlapping ellipses, are chosen. In each pixel of the selected ellipses, the Harris cornerness measure in computed at the scale re-projected from the orbital image scale of the landmark and the position of the maximum is the descent match for the landmark. Finally, the entire set of matches is processed through the RANSAC algorithm, to look for outliers with respect to the projective camera model [29].



Variable	$3\sigma_V$	$3\sigma_{TD}$
Attitude/Yaw (deg)	0.5	0.5
Attitude/Pitch (deg)	0.7	0.7
Attitude/Roll (deg)	0.9	0.9
Velocity/X-axis (m/s)	0.7	1.2
Velocity/Y-axis (m/s)	0.8	1.2
Velocity/Z-axis (m/s)	0.9	0.9
Velocity norm (m/s)	1.0	1.1
Position/X-axis (m)	12.9	35.3
Position/Y-axis (m/s)	11.8	32.9
Position/Z-axis (m)	10.1	23.9
position norm (m)	12.0	36.1

Figure 17 - Monte-Carlo results: position error plot (left) and error statistics at the time of the last visual measurements (V) and at touchdown (TD)

This solution was tested in a 100-run Monte-Carlo analysis, dispersing the 3-sigma values of the initial errors by 1 deg, 10 m/s, and 100 m per axis respectively for attitude, speed and position. The trajectory was an Apollo-like Lunar approach, phased starting at 2000 m of altitude with a 1024x1024 camera image sensor covering a 70-deg field of view. The

BOX 3 – Bundle adjustment and aero triangulation

Bundle adjustment (BA) [84] designates the method designed to simultaneously refine the position of K 3D points and the parameters of N cameras (attitude, position and intrinsic parameters in the most general case) given image measurements. BA is formulated in a basic way as the minimization of a non-linear least squares criterion, measuring the total re-projection errors in all images:

$$J\left(\left\{\mathbf{C}_j\right\}_{j=1\dots K},\left\{\mathbf{P}_i\right\}_{i=1\dots N}\right)=\sum_{i}^{N}\sum_{j=1}^{K} v_{i,j}\left(\mathbf{u}_{i,j}-\mathcal{P}\left(\mathbf{C}_j,\mathbf{P}_i\right)\right)^2$$

where vi,j is a binary variable indicating if the i-th landmark is visible in the j-th view, $\mathbf{u}_{i,j}$ is the image feature corresponding to the projection of the i-th 3D landmark on the j-th image, $\mathbf{C}_j$ are the parameters of the j-th view, $\mathbf{P}_i$ are the parameters of the i-th 3D landmark and $\mathcal{P}$ is the mathematical camera model (see box 2). The maximum likelihood formulation can evidently take into account other information sources, such as prior camera positions given by (D) GPS or prior 3D landmark positions given by a map. In the same way, prior error covariance can be taken into account by replacing the L2-norm by the Mahalanobis norm. Aero-triangulation is the special case of bundle adjustment when the positions of some 3D features are known in a global frame.

The mathematical background to solve such criterion is well known (Gauss-Newton, Levenberg-Marquardt or Trust region techniques). The difficulties come from two aspects: the poor robustness of the least squares minimization scheme to outliers and the computational cost in O(M^3), where M is the number of parameters to be refined simultaneously. The first problem is addressed through robust least squares, like M-estimators, which replace the L2 penalty function with an unnecessary convex function more tolerant to large residual errors. The second pitfall is by-passed by taking into account the special structure of the graph associating the refined parameters and the full set of image measurements. Indeed, since an image measurement depends only on one camera parameter and on one structure parameter, the graph is extremely sparse. This property is used to considerably reduce the computational cost. For practical purposes, the (6K+ 3N) global problem is transformed into a combination of one problem with 6K variables and N problems with 3 variables.

This algorithm is commonly called fullSLAM in the robotics community, in contrast to the EKF-SLAM which tends to solve the same criterion in a sequential way.

terrain had a 500-m height range and a 20-deg illumination difference in azimuth was introduced between the descent and orbital image, the latter being taken at a 50-km altitude. The results are shown in figure 17. All of the runs converged and touchdown 3-sigma error statistics are below 40 m in position, which is compatible with the 100-m pinpoint landing requirements. It must be noticed that below 200 m of altitude, 50 s after start, no landmark can be matched anymore, because of the limited map density and thus an inertial error drift occurs. At the end of the visual phase, the position 3-sigma error was of only 12 m, which can be considered as the actual performance of the vision system.

Environment Mapping for absolute navigation and mission-planning

Previous parts addressed vision subsystems directly involved in the control or navigation of intelligent vehicles. Mission planning and some vision-based navigation functions depend on precise maps of the flown over areas. These maps are generally provided by geographic information authorities (such as IGN in France, BkG in Germany, etc.) or by geosensing companies. However, this data could be outdated – for example, after a natural or industrial disaster –, partial– orthoimages are 2D-only, digital terrain model (DTM) do not contain objects above ground – or available in a resolution not well-suited to processing (a drawback for image registration technique for absolute navigation). To bypass these limitations, UAVs offer a low-cost solution to collect data (image, video, lidar) necessary to update maps. Note that some companies already offer this kind of service [4][69].

This section is consecrated to the environment mapping from UAVs and is illustrated through two applications. The first is relative to geosensing and photogrammetry, in order to provide DSM and orthomosaics, as in [15][26]. The second is relative to onboard mapping, to plan an unattended safe landing. In both cases, the UAVs fly above the obstacles and GPS reception is supposed to be perfect.

Offline mapping from video and lidar data

Whatever the aerial vehicle considered, an offline environment mapping task follows a well-established scheme: flight dedicated to the acquisition of heterogeneous time-stamped data (IMU,GPS, video, lidar, position of landmarks, etc.) and refinement of the trajectory estimated by the IMU/GPS navigation system thanks to exteroceptive sensors and environment modeling [15][26][49]. The proposed processing chain is no exception to the rule.

In our case, the data is acquired from the Onera UAV platform, ReSSAC [28]. This UAV is based on the Yamaha Rmax (gross mass 100 kg), equipped with a hybrid IMU/GPS-RTK navigation filter, a standard grayscale industrial camera and a 4-layer lidar scanner (SICK LD-MRS).

After a resynchronization of exteroceptive data with attitude/position information by trajectory interpolation, the video data is processed to correct the UAV 6D-trajecory (attitude and position) by bundle adjustment (see box 3 for details). Bundle adjustment uses two kinds of image features: Harris points [34] tracked by KLT [80] and SIFT [53] features matched between loop-closing frames (when the UAV fly over an area that has already been visited). The huge number of frames (more than 4000 for the example in figure 18) leads us to adopt a hierarchical bundle adjustment process. First, the trajectory is reduced to a graph of key-frames selected automatically according to an overlapping ratio deduced from the initial viewing parameters. Each node represents a key-frame and is linked to the previous and next key-frame. The graph contains some loop-closing links between temporally-distant key-frames. The loop closing detection is also based on the predicted overlap ratio between key-frames thanks to the good confidence in the UAV trajectory parameters. This graph defines the skeleton of the trajectory and a first bundle adjustment refines the parameters associated to this graph (viewing parameters of the keyframes plus position of 3D points tracked on the key-frames). In the second step, the trajectory is divided into non overlapping segments of views, delimited by key-frames and each segment is processed by a local bundle adjustment.

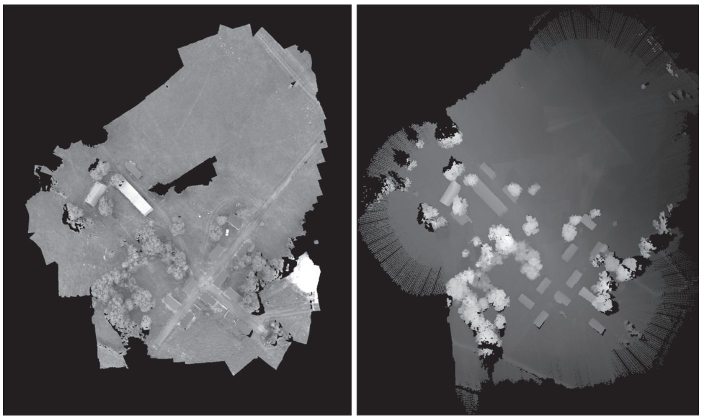


Figure 18 - Ortho-mosaic and Digital surface model of the Caylus combat camp from video and lidar data acquired by Onera ReSSAC UAV. The UAV states are refined by video aero-triangulation. Note that a lidar sensor has a greater lateral field of view than a video sensor. Thus, the ortho-mosaic does not entirely cover the DSM.

Thanks to lidar, we have access to precise 3D measurements, we do not need to infer the 3D information by image processing (higher resolution but more parameters to set). The lidar measurements are converted to 3D points localized in the global frame (relative to one point in the area selected as (0,0,0), while the axes are defined in a classical North-East-Down order). The DSM, corresponding to a regular sampling of the horizontal plane, is built by taking the altitude of the higher lidar 3D points in each cell. The orthomosaic, superimposable to the DSM, is achieved by projecting the DSM and taking into account geometric visibility, thanks to a z-buffer. Figure 18 shows the main output of our processing chain.

In its current version, our processing chain combines lidar data and video data in a suboptimal way, each sensor being used for distinguishable tasks. Work is in progress to introduce telemetric measurements within the aerotriangulation process. In the future, it would be interesting to combine these two types of data for environment modeling too.

Online obstacle mapping for safe landing planning

In the projects PRF ReSSAC [28] and PEA Action [7], a task assigned to the UAV is to explore an area to detect obstacles over ground. This obstacle map must be built online to plan a safe landing in the vicinity of an object of interest or to aid an unmanned ground vehicle in this navigation task.

For this task, we consider a monocular downward-looking camera and two restrictive assumptions: the ground is locally plane and the ground occupies quite a large part of the image. Under these assumptions,

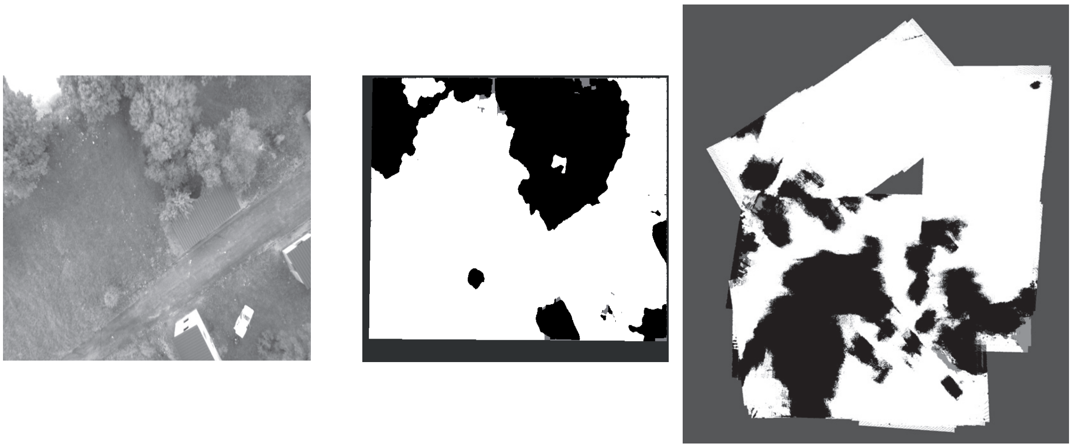


Figure 19 - Detection of obstacles above ground by segmenting optical flow. On the left: the reference image; in the center, the detection map (white: safe; black: obstacle; light gray: unknown; dark gray: non-overlapping regions)

obstacle detection is equivalent to finding an image area for which image motion (between two successive views) cannot be described by the majority homography. Our work is quite similar to [14]. As in this latter reference, a first step uses the matching of Harris corners [34] between two views to infer the majority homography, thanks to a robust least square method (Least Median of Squares[75]). Our method differs from [14] with the obstacle classification step. In [14], authors compute the correlation between the reference view and the second image warped into the reference, thanks to estimated homography (this warped image is a so-called displaced frame difference). On our side, we have developed two concurrent methods, based on the comparison of the “true” optical flow and the estimated homographic optical flow. The first is based on the Odobez work [65]: the proposed criterion computed from the DFD approximates the previous mentioned difference. The second uses the CPU-based efficient quasi-dense optical flow algorithm proposed by Lhuillier et al in [51]. In this case, the detection is directly obtained by optical flow comparison. In both cases, a threshold criterion produces ternary maps (obstacle / free / unknown). The computation times of these two methods are similar, between 2 and 3 frames per second on a 2.5Ghz Intel Core2 Duo (the algorithm is not multi-threaded) on 640x480 images. The processing may seem slow, however, this frequency permits a better baseline to be acquired between two successively processed frames. Figure 16 presents the result of our method, based on the Quasi-dense optical flow. Here, the ground occupies a large part of the image and the detection looks precise, the hole between the house and the trees (near of the image center) is detected as non-obstacle. These individual detection maps are then associated in a global map, thanks to viewing parameters to drive a motion planning algorithm (map on the right in figure 19).

The same video sequence has been processed to obtain the obstacle map on the right in figure 19 and the DSM in figure 18. A comparison could be made and the estimated obstacle map is globally consistent with the DSM – at the same time, in the ground area and in the above-ground elements – despite the enlargement of the obstacle footprint (the pixels are projected onto the map under the hypothesis of a plane scene) or some misalignment due to erroneous viewing parameters.

Conclusion

We have presented here several contributions for navigation, mainly carried out in the context of Onera’s research projects PRF SPIDER and PR AZUR, more precisely described in box 4. We have shown that the three control levels of an automatic system could require perception functions. This interaction between the control and the perception functions involves the processing time and, consequently, the nature of the information provided by the image processing.

For the lowest control level, the image processing provides 2D-only information, such as optical flow (dense or parametric) or parametric image transform (homography). The emphasis is placed on control aspects. At an intermediary level, we are interested in the vision-based relative navigation. Videos are processed in order to provide a geometrically-consistent trajectory and environment modeling. This 3D information must be inferred from passive or active sensors. This topic is addressed outside the context of vehicle control. Lastly, we have presented some work for replacing GPS measurements and for long-term mapping. Replacing GPS requires reference maps to register an image on it. As is frequently the case in image processing, the problem can be addressed by using image features or the whole image. Long-term mapping provides a useful model for – online or offline – mission planning and for GPS replacement. By taking into account all available measurements in a global process, offline mapping offers the more precise results.

In the future, two technologies will make it possible to go further in the autonomous navigation of aerial vehicles.

The first concerns the generalization of massively-parallel architectures. Image processing is well suited to this kind of architecture because many of the techniques rely on image filtering, for example to identify image features. Thanks to increasingly energy-efficient electronics, solutions are being combined on the same silicon piece multi-core CPU and a Graphical Processing Unit (GPU), promising increasing computing power.

The second concerns the sensors and especially the 3D sensors. The Microsoft Kinect is a good example of a technological breakthrough. It is a lightweight and energy-efficient device that has been largely adopted for indoor robotics (aerial or not). Its main drawback is its active nature, which limits its usage domain to the indoor one. Also, for outdoor use, the development of 3D compact passive sensors, like the one proposed in the SPIDER project (see box 4), seems a very promising way ■

BOX 4 – Perception for navigation themes at Onera

The themes of perception for automatic vehicle navigation are articulated around two internal research projects with separate finalities. The PRF SPIDER (first subsection) is concerned with the development of perception components (sensor and calculators) useful for UAV navigation. The PR AZUR (second subsection) is oriented onboard integration and in-flight demonstration with specific development around control and guidance using perception algorithms.

SPIDER: co-designing the «eyes» of future micro-UAVs

A major issue in micro-UAV concepts is to design their eyes, i.e. integrated «perception devices», made of sensors and microcomputers, which should not only provide good images, but also directly provide good information for autonomous behavior. This is the goal of Onera's internal project SPIDER, a French acronym which could be translated as «Small Perception and Interpretation Devices for Urban EnviRonment». To start with, SPIDER integrates researchers in the domains of optics, vision and control and promotes a «co-design» approach. Co-design amounts to evaluating the end-to-end performance of a perception device, including optics, vision algorithm and control parameters, so as to search for a global optimum to the perception problem at hand. This approach tends to reduce the overfitting issues associated with traditional sequential design. The main objective of SPIDER is to produce demonstrations of the proposed perception device concepts. Among the most interesting SPIDER demonstrators is CAM3D, a passive monocular sensor with 3D capability, based on the «depth-from-defocus» paradigm: preliminary results, extracted from the PhD work of Pauline Trouvé (Onera) [85] are presented in figure 22. This figure shows a realistic and coherent raw depth estimation, using a criterion called GL developed in the DTIM. It shows a good localization of depth discontinuities in most cases. Even the incised trunk is detected. The median filter efficiently removes the noise, with some artifacts on the discontinuities.

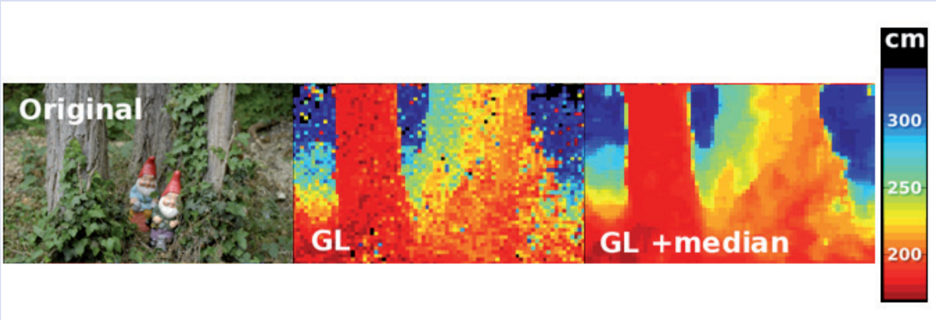


Figure B4-01 - Output of the CAM3D concept. On the left, the RGB image. In the center, the raw depth map after a depth-from-defocus process. On the right, the depth map after a median post-processing. Depth varies between 1.5m and 3.5m according to the indicated colormap

AZUR: Autonomous navigation of UAV in an urban zone.

The AZUR project is aimed at making an onboard navigation software system of a VTOL-type UAV for its fully-autonomous/semi-autonomous operation in an urban environment. As illustrated in the figure below, the system is a closed-loop chain of perception, decision and action. In order to ensure flight safety, onboard perception is mandatory to obtain the current situation of both the UAV and of the environment (obstacles, wind conditions, etc.). In the AZUR project, the following four function modules will be developed:

- Real-time environment mapping and path planning;
- Obstacle detection and reactive avoidance;
- Navigation without GPS;
- Wind gust estimation and compensation.

Especially, the first three apply active and/or passive vision-based control approaches. For example, optical flow-based visual servoing for obstacle avoidance, and visual odometry for GPS-free navigation.

These modules will be integrated into one complete navigation system and implemented onboard one or more of the Onera UAV experimental platforms. Flight demonstration of their safe autonomous operation in an obstacle field is expected at the end of the project.

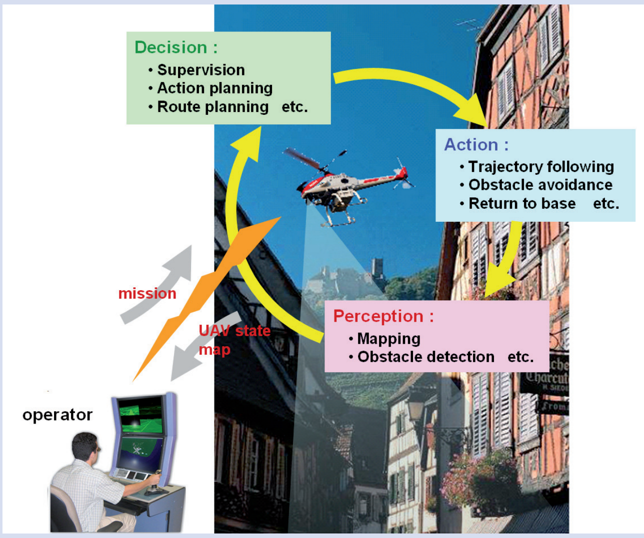


Figure B4-02 - UAV on-board navigation system

Acronyms

BA (Bundle Adjustment)
CAM3D (CApteur passif Monovoie à capacité 3D)
CPU (Central Processing Unit)
DEM (Digital Elevation Model)
DSM (Digital Surface Model)
EKF (Extended Kalman Filter)
FPGA (Field-Programmable Gate Array)
GPS (Global Positioning System)
GPU (Graphics Processing Unit)
IMU (Inertial Measurement Unit)
OF (Optical Flow)
PR AZUR (Projet de Recherche Autonomie en Zone URbaine)
PRF SPIDER (Projet de Recherche Fédérateur Système de Perception et d'Interprétation Dynamique en Environnement uRbain)
SLAM (Simultaneous Localization and Mapping)
RGBD (Red-Green-Blue-Depth (camera))
UAV (Unmanned Aerial Vehicle)
VTOL (Vertical Take-Off and Landing)

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Synthesis of plans or policies for controlling dynamic systems

To be properly controlled, dynamic systems need plans or policies. Plans are sequences of actions to be performed, whereas policies associate an action to be performed with each possible system state. The model-based synthesis of plans or policies consists in producing them automatically starting from a model of the physical system to be controlled and from user requirements on the controlled system. This article is a survey of what exists and what has been done at Onera for the automatic synthesis of plans or policies for the high-level control of dynamic systems.

A high-level reactive control loop

Aerospace systems have to be controlled to meet the requirements for which they have been designed. They must be controlled at the lowest levels. For example, an aircraft must be permanently controlled to be automatically maintained at a given altitude or to go down to a given speed. They must be controlled at higher levels too. For example, an autonomous surveillance UAV must decide on the next area to visit at the end of each area visit (highest navigation level). After that, it has to build a feasible trajectory allowing it to reach the chosen area (intermediate guidance level). Then this trajectory is followed using an automatic control system (lowest control level).

At any level, automatic control takes the form of a control loop as illustrated by figure 1. At any step, the controller receives observations from the dynamic system and sends it back commands; commands result in changes in the dynamic system and then in new observations and commands at the next step.

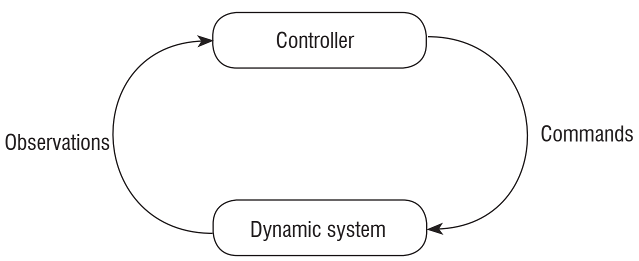

Figure 1 - Control loop of a dynamic system

At the lowest levels, for example for the automatic control of an aircraft, the dynamic system is usually modelled using a set of differential equations (domain of continuous automatic control [29]). However, at the highest levels, for example for the automatic navigation of an UAV, it is more conveniently modelled as a discrete event dynamic system (domain of discrete automatic control [14]): instantaneous system transitions occurring at discrete times; if the system is in a state s and an event e occurs then it moves instantaneously to a new state s' and remains in this state until the next event occurs.

In some cases, these transitions can be assumed to be deterministic: there is only one possible state s' following s and e. In other cases, due to uncertain changes in the environment, actions of other uncontrolled agents, or uncertain effects of controller actions, they are not deterministic: there are several possible states s' following s and e. For example, the result of an observation action by an UAV may depend on atmospheric conditions.

In some cases the controller has access to the whole system state at each step (full observability). However, in many cases it only has access to observations that do not allow it to know exactly the current system state (partial observability). For example, an automatic reconfiguration system may not know the precise subsystem responsible for faulty behavior but it must act in spite of its partial knowledge. In certain particular cases no observation is available (null observability).

In many cases, the system is assumed to run infinitely: in fact, its death is not considered. However, in some cases it is assumed to stop when reaching certain conditions. This is the case when we consider a specific mission for an UAV which ends when the UAV lands at its base.

User requirements on the behavior of the controlled system may take several forms. Most generally, they take the form of properties (constraints) to be satisfied by the system trajectory (sequence of states followed by the system), or of a function of the system trajectory to be optimized. Usual properties are safety and reachability properties: a safety property must be satisfied at any step whereas a reachability property must be only satisfied at a certain step. The requirement that the energy level on board a spacecraft must remain above a minimum level is an example of a safety property. The fact that an UAV must visit a given area is an example of a reachability property.

The most general form of a controller is a policy which associates with each pair consisting of an observation o and a controller state cs, another pair consisting of a command c and a new controller state cs' (see figure 2).[1] The controller state is useful for recording relevant features of past observations and commands, as well as current objectives. Note that command c and controller state updating cs' are deterministic whereas system state transition s' may not be.[2] In the particular case of a finite trajectory with determinism or with non-determinism without observability (when observability is useless or impossible), a controller may take the simpler form of a plan which is a sequence of commands.

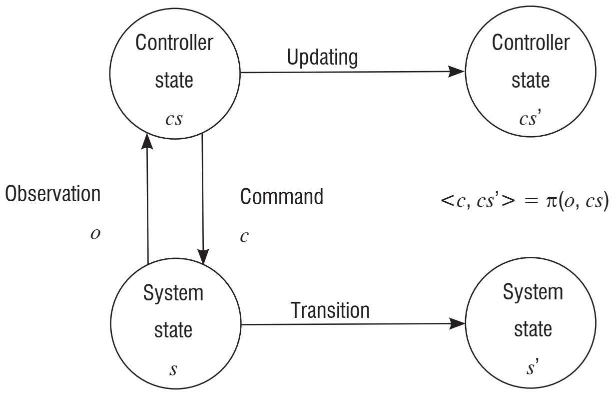

Figure 2: Controller implementing a policy π

The main question of discrete automatic control is then "how to build a controller (a policy or a plan) that guarantees that requirements on the controlled system are satisfied, possibly in an optimal way?".

To do this, three main approaches can be distinguished: (1) manual design, (2) automatic learning, and (3) automatic synthesis. The first approach, which is by far the most usual, assumes the existence of human experts or programmers who are able to define a controller under the form of decision rules which point out what to do in each possible situation, for each pair (observation, controller state). Model checking techniques [18] can then be used to verify that the resulting controller satisfies requirements. The second approach, which is being used more and more, consists in automatically learning a controller from experience, that is, from a set of tuples (observation, controller state, command, effects), which can be obtained by running the system or by simulating it [47]. The third approach, which is the most used at Onera for the control of aerospace systems because it offers the best guarantees in terms of requirement satisfaction, consists in automatically synthesizing a controller from a model of the dynamic system, the controller and the requirements on the controlled system. This third option is the approach we develop in this article.

Control synthesis modes

When it is embedded in an aircraft or spacecraft, the controller may be strongly limited in terms of memory and computing power. In spite of these limitations it has to make reactive decisions or at least make decisions by some specified deadlines. For example, the next area to be visited by an UAV and the trajectory that allows this area to be reached must be available by the end of the visit of the current area.

To satisfy these requirements the most usual approach consists in synthesizing the controller off-line, before execution. As soon as it has been built, the controller can be implemented and then reactively executed on board.

However, synthesizing a controller off-line requires that all the possible situations be taken into account. Because the number of possible situations can quickly become astronomical (settings with 10^{100}, 10^{500}, or 10^{1000} possible situations are not rare), difficulties quickly arise in terms of controller synthesis, memorization, and execution.

To overcome such difficulties an option is available that consists in synthesizing the controller on-line on-board: given the current context, the number of situations to be considered can be dramatically reduced; if computing resources are sufficient on-board, the synthesis of a controller dedicated to the current context may be feasible by the specified deadlines; as long as the current context remains unchanged, this controller remains valid; as soon as the context changes, a new controller is synthesized. See [60] for a generic implementation of such an approach. Anytime algorithms [72], which quickly produce a first solution and try to improve on it as long as computing time is available, may be appropriate in such a setting.

When the state is fully observable and the possible state evolutions can be reasonably approximated by a deterministic model, at least over a limited horizon ahead, an option consists in (i) synthesizing a simpler controller under the form of a plan over a limited horizon, (ii) keeping with this plan as long as it remains valid (no violated assumptions and a sufficient horizon ahead taken into account), and (iii) replanning as soon as it becomes invalid. Such an option (planning/replanning) is widely used because of its simplicity and efficiency. See [31] for an example of application to the control of Earth observation satellites.

Another option, close to the previous one and to the model predictive control [24] approach developed in the domain of continuous automatic control, consists, at each step, in (i) observing the current state, (ii) synthesizing a controller in the form of a plan over a limited horizon (reasoning horizon), (iii) applying only the first command of this plan (decision horizon), and (iv) starting again at the next step over a sliding horizon. A simple decision rule (valid, but non optimal) is applied when no plan has been produced. See [44] for a generic

[1] This approach of control differs from the approach adopted by the pioneering works on discrete control [53] which consider that the role of control is not to specify a command, but to restrict the set of acceptable commands.

[2] We do not consider in this article the case of non deterministic controllers which select commands in a non deterministic stochastic manner.

implementation of such an approach and [5] for an example of application to the autonomous control of an Earth observation satellite.

Models

The automatic controller synthesis approach requires models of the dynamic system and of the requirements on the controlled system.

Model of the dynamic system

Dynamic systems are usually modelled using:

- a finite set S of possible states;
- a finite set O of possible observations;
- a finite set A of possible actions;
- an initialisation model I which defines possible initial states;
- an observation model Om which defines possible state-observation pairs;
- a feasibility model F which defines feasible state-action pairs;
- a transition model T which defines possible state transitions.

When transitions are deterministic, T is a function from $S{\times}A$ to S. When they are not deterministic, T is a relation over $S{\times}A{\times}S$. When probabilistic information is available, T is a function which associates with each element of $S{\times}A$ a probability distribution over S. Similarly, Om may be defined by a function from S to O, by a relation over $S{\times}O$, or by a function which associates with each element of S a probability distribution over O. I may be defined by an element of S, a subset of S or a probability distribution over S. Finally, F is defined by a relation over $S{\times}A$.

It must be emphasized that the transition model is here assumed to be Markovian: the next state s' depends only on the current state s and action a; it does not depend on previous states and actions. When this assumption is not satisfied it is necessary to add relevant features of past states and actions in the state definition to get it satisfied. It must be stressed too that, in this presentation, a state includes the system state and the controller state. Hence, with regard to figure 2, the transition model includes system state transition and controller state updating.

Requirements on the controlled system

Finally, user requirements on the controlled system are modelled using a requirement model R which may take several forms:

- R may be a subset of S which defines the set of acceptable final states, also called goal states (reachability property);
- R may be a relation over $S{\times}A{\times}S$ which defines the set of acceptable transitions (safety property), not to be mistaken for the set T of possible transitions, previously defined in the model of the dynamic system;
- R may be a function from $S{\times}A{\times}S$ to the set of reals which associates a local reward with each transition; the total reward associated with a trajectory is then the sum of the local rewards associated with the successive transitions.

More complex requirements on the system trajectories may be expressed using temporal logics [20] or non Markovian rewards that are rewards on state trajectories [63].

Compact representations

Usually, sets S, O, and A of states, observations, and actions are compactly defined using finite sets of state, observation, and action variables whose domains of value are finite (factored representation). For example, if Sv is the set of state variables, S is defined as $\prod_{v \in Sv} D(v)$, where $D(v)$ is the domain of v. Similarly, initialisation, observation, feasibility, and transition relations are compactly defined using constraints [54] or decision diagrams [13]. Initialisation, observation, and transition probability distributions may also be compactly defined using Bayesian networks [40], valued constraints [55] or algebraic decision diagrams [2].

Usual frameworks

For example, in the classical AI planning framework (Artificial Intelligence planning [28]), the initialisation model is defined by a state (only one possible initial state), the feasibility model by action preconditions, the transition model by deterministic action effects, and the requirement model by a set of goal states. The objective is to build a plan that allows a goal state to be reached. Observation is useless because of determinism. Specific languages, such as PDDL [23, 27], have been developed in the context of the International Planning Competition (IPC) to allow users to express models in a compact and natural way.

Another example, in the classical MDP framework (Markov Decision Processes [52]), is where initialisation and transition models are defined by probability distributions, there is no observation model (assumption of full observability) and the requirement model has the form of additive local rewards. The objective is to build a policy that maximizes the expected total reward over finite horizons or the expected discounted total reward over infinite ones (reward geometrically decreasing as a function of the step number). In the POMDP framework (Partially Observable MDP [37]), the observation model is defined by a probability distribution.

In the goal MDP framework [71, 61], which is a hybrid between AI planning and MDP, a set of goal states is added to the MDP definition and local rewards are replaced by costs. The objective is to build a policy that minimizes the expected total cost to reach a goal state.
Finally, in a framework that can be referred to as the logical MDP framework [8, 51], initialisation, observation, transition, and requirement models are defined by relations. The objective is to build a policy that guarantees that reachability and/or safety requirements are satisfied in spite of non determinism and partial observability.

Other models

It must be emphasized that, although these models are generic, many real problems of synthesising plans or policies in the aerospace domain are more conveniently modeled using different frameworks, popular in the Operations Research community: scheduling, resource assignment, knapsack, shortest path, or traveling salesman problems [3, 39, 43]. For example, the main objective of plan synthesis is to build a sequence of actions allowing a goal to be reached. However, when planning activities for an Earth observation satellite, the problem is not to discover the sequence of basic actions allowing an area a to be observed: one knows that is necessary to set the instrument ON, to point the satellite towards the beginning of a during a's visibility window, to start observing, to memorize data, and then to download it using a station visibility window. The HTN framework (Hierarchical Task Network [21, 56]) may be used to describe such a breakdown of a task into sub-tasks. The main problem is to organize observations over time and resources in order to perform a maximal subset of them of maximum value. In these problems, time and resource management is central and an explicit representation of the system state may be useless. See [45] for an example.

It must be however stressed that standard Operations Research problems rarely allow real problems to be completely and precisely modelled. For example, many problems are over-constrained scheduling problems with complex time and resource constraints to be satisfied and a complex optimization function to be optimized. See [30] for an example.

It must be emphasized too that many problems in the aerospace domain combine action planning [28] and motion planning [42]. For example, inserting the visit of an area into the activity plan of an UAV requires checking the feasibility of the trajectory allowing the UAV to reach this area and to compute the effects of this movement, for example in terms of energy. See [33] for the proposal of a generic scheme for cooperation between action and motion planning.

To sum up, many real problems appear to be complex hybrids of action planning, motion planning, and task scheduling. The CNT framework (Constraint Network on Timelines [67]) has been developed to try and model them as well as possible. It extends the basic CSP framework (Constraint Satisfaction Problem [54]) by defining horizon variables that represent the unknown number of steps in system trajectories and by defining dynamic constraints as functions which associate a set of classical CSP constraints with each assignment of the horizon variables.

Optimality equations

Optimality equations, also called Bellman equations [6], allow satisficing or optimal policies to be characterized. In the MDP framework over infinite horizons, they can be defined as follows.

Let $I(s)$ be the probability of being initially in state s, $F(s,a)$ be a Boolean function which returns true when action a is feasible in state s, $T(s,a,s')$ be the probability of being in state s' after applying action a in state s, $R(s,a,s')$ be the local reward associated with this transition, and $\gamma \in [0,1[$ be the discount factor.

Let $V^*(s,a)$ be the optimal expected total reward it is possible to obtain when starting from state s and applying action a, $V^*(s)$ be the optimal expected total reward it is possible to obtain when starting from state s, V^* be the optimal expected total reward it is possible to obtain taking into account the possible initial states, and π^* be an optimal policy. It can be shown that the following equations must be satisfied:

$$\forall s \in S, \forall a \in A / F(s,a) : V^*(s,a)$$
$$= \sum_{s' \in S} T(s,a,s').(R(s,a,s') + \gamma.V^*(s'))$$

$$\forall s \in S : V^*(s) = \max_{a \in A/F(s,a)} V^*(s,a)$$
$$\forall s \in S : \pi^*(s) = \arg\max_{a \in A/F(s,a)} V^*(s,a)$$
$$V^* = \sum_{s \in S} I(s).V^*(s)$$

While the values $V^*(s,a)$, $V^*(s)$, and V^* are the only solutions of this set of equations, several associated optimal policies are possible.

In the goal MDP framework, there is no discount factor, $V^*(s)=0$ for any goal state s, and maximization is replaced by minimization.

In the logical MDP framework, these equations can be reformulated as follows.

Let $I(s)$ be true when s is a possible initial state, $F(s,a)$ be true when action a is feasible in state s, $T(s,a,s')$ be true when s' is a possible state after applying action a in state s, and $R(s,a,s')$ be true when this transition is acceptable (safety properties).

Let $V^*(s,a)$ be true when it is possible to satisfy the safety properties when starting from state s and applying action a, $V^*(s)$ be true when it is possible to satisfy the safety properties when starting from state s, and π^* be a satisfying policy. It can be shown that the following equations must be satisfied:

$$\forall s \in S, \forall a \in A / F(s,a) : V^*(s,a)$$
$$= \wedge_{s' \in S} (T(s,a,s') \rightarrow (R(s,a,s') \wedge V^*(s')))$$

$$\forall s \in S : V^*(s) = \vee_{a \in A/F(s,a)} V^*(s,a)$$
$$\forall s \in S : \pi^*(s) = \text{argtrue}_{a \in A/F(s,a)} V^*(s,a)$$
$$\forall s \in S : I(s) \rightarrow V^*(s)$$

Algorithms

Dynamic programming

Dynamic programming algorithms [6] make direct use of the optimality equations to produce satisfying or optimal policies. The most popular variant, referred to as value iteration, approximates better and better values $V^*(s)$, starting from any initial values $V_0(s)$. In the classical MDP framework, at each algorithm iteration step $i>0$, values are updated in the following way:

$$\forall s \in S, \forall a \in A / F(s,a) : V_i(s,a)$$
$$= \sum_{s' \in S} T(s,a,s').(R(s,a,s') + \gamma.V_{i-1}(s'))$$

$$\forall s \in S : V_i(s) = \max_{a \in A/F(s,a)} V_i(s,a)$$

It can be shown that values $V_i(s)$ asymptotically converge to $V^*(s)$. Practically, the algorithm stops when $\max_{s \in S} |V_i(s) - V_{i-1}(s)|$ is below a given threshold. When it stops at step i, a policy π can be extracted using the following equation:

$$\forall s \in S : \pi(s) = \arg\max_{a \in A/F(s,a)} V_i(s,a)$$

In the logical MDP framework, initial values $V_0(s)$ are all true and convergence is reached in a finite number of iterations.

These algorithms are the most natural way of getting an optimal policy when the number of states remains reasonably small. However, because the number of states is an exponential function of the number of state variables, they may quickly become impracticable.

To overcome such a difficulty, special structures can be used inside dynamic programming algorithms. In the logical MDP framework, binary decision diagrams (BDD [13]), allowing a Boolean function of Boolean variables to be represented, can be used to represent relations compactly and manipulate them [17]. This technique can be extended to classical MDP using algebraic decision diagrams (ADD [2]), allowing a real function of Boolean variables to be represented.

Heuristic search

Whereas dynamic programming algorithms consider all possible states, heuristic search algorithms consider only those that are reachable from the possible initial states by following the policies that are considered: a potentially very small subset of the set of possible states.

Although these algorithms are not limited to AI Planning problems, they can be easily presented in this framework. In AI Planning, we have one possible initial state, positive action costs, deterministic transitions, and a set of goal states. The problem can be formulated as a shortest path problem in a weighted oriented graph where nodes are associated with states, arcs with transitions, positive weights with action costs: a shortest path is sought from the node associated with the unique initial state to any node associated with a goal state.

Efficient algorithms exist to produce shortest paths from an initial node n_0 to any node in weighted graphs with positive weights, such as the well-known Dijkstra algorithm [19]. Let $W(n,n')$ be the weight of the edge from node n to node n'. This algorithm incrementally builds a tree of shortest paths from n_0 to any node n, rooted in n_0. At each algorithm step, with any node n, are associated an upper bound $V(n)$ on the minimum length to go from n_0 to n, and the parent node $P(n)$ of n in the current tree. Values $V(n)$ are initialized with $+\infty$, except 0 for the initial node. Parent nodes $P(n)$ are initialized with $\varnothing$. At each algorithm step, the algorithm visits a new node. The selected node is a node of minimum value $V(n)$. For each node n' that has not been visited yet and can be reached directly from n, such that $V(n)+W(n,n')<V(n')$, $V(n')$ is updated to $V(n)+W(n,n')$ and $P(n')$ to n. The algorithm stops when all nodes have been visited. It is guaranteed that, for each node n, $V(n)$ is then the minimum distance from n_0 to n. The associated shortest path can be built backward using $P(n)$. This algorithm visits only the nodes that are reachable from n_0.

However, when we search for shortest paths from an initial node to a set of goal nodes, more efficient algorithms exist, such as the well-known A^* algorithm [35]. This algorithm works as the Dijkstra algorithm does, except that values $V(n)$ are replaced by values $V'(n)$ which are the sum of two values: a value $V(n)$ which is an upper bound on the minimum distance from n_0 to n, and a value $H(n)$ which is a lower bound on the minimum distance from n to any goal node. Values $V(n)$ are initialized and updated the same way as they are in the Dijkstra algorithm. As for values $H(n)$, they are assumed to be given by an admissible (optimistic) heuristic function, null for any goal node. At each algorithm step, the selected node is a node of minimum value $V'(n)$. If the heuristic function is monotone $(\forall n,n': H(n) \leq H(n')+W(n,n'))$ then a node cannot be revisited, but if it is not then a node may be visited several times. The algorithm stops when the selected node is a goal node. It is guaranteed that the value $V(n)$ of this node is the minimum distance from the initial node to any goal node. With regard to the Dijkstra algorithm, the main advantage of this algorithm is its focus on goal states via the heuristic function. Its efficiency strongly depends on this heuristic. The better the heuristic function $H(n)$ approximates the minimum distance from n to any goal node, the fewer nodes are visited. The Dijkstra algorithm is a particular case of A^* where the heuristic function is null for any node.

The most efficient algorithms for solving AI planning problems, such as HSP (Heuristic Search Planner [11]) or FF (Fast Forward [36]), combine sophisticated variants of A^* with powerful heuristic computations.[3] The heuristic function is automatically built by solving specific problem relaxations at each node of the search. Some of these heuristics are admissible (thus yielding optimal plans) as the optimum of any problem relaxation is a lower bound on the optimum of the original problem. The YAHSP planner (Yet Another Heuristic Search Planner [68]) uses variants of these principles as well as a lookahead strategy which causes the planner to focus more quickly on promising parts of the graph. It must be stressed that the graph is never explicitly built. It is only explored as and when required by the effective search.

Heuristic search can be generalized to planning under uncertainty. For example, the LAO^* algorithm [34] solves goal MDP problems via a combination of heuristic forward search and dynamic programming. The RFF algorithm (Robust FF [59]) solves the same problems using successive calls to FF: a deterministic model of the goal MDP is first built by considering the most likely initial state and, for each state and each feasible action, the most likely transition; a plan is built using this deterministic model; then, this plan, which is a partial policy, is simulated using the original non deterministic model; for each reachable state s that is not covered by the current policy, a plan is built from s using the deterministic model, and so on until all reachable states or nearly of them are covered by the current policy. If all reachable states are covered then the resulting policy guarantees goal reachability but may not be optimal.

Greedy search

Greedy search is a very simple technique for dealing with combinatorial optimization problems. It consists in making successive choices, following a given heuristic, without ever reconsidering previous choices. For example, in AI planning, it is possible to systematically choose as a next node a node n that minimizes the heuristic function $H(n)$. It is clear that this method offers no guarantee in terms of goal reachability and optimality.

However, repeated greedy searches, combined with learning, can offer these guarantees. For example, the $LRTA^*$ algorithm (Learning Real Time A^* [41]) solves shortest path problems by performing a sequence of greedy searches. Each search starts from the initial node n_0 and greedily uses a heuristic function V which is a lower bound on the minimum distance to a goal node. V is initialized by any admissible (optimistic) heuristic. When the current node is n, a node n' that minimizes $W(n,n')+V(n')$ is selected, $V(n)$ is updated to $W(n,n')+V(n')$, and n' becomes the current node. The search stops when the current node is a goal node. A new search can start using the current heuristic function V. It can be shown that, search after search, this function converges to the minimum cost to reach a goal node. This algorithm can be straightforwardly generalized to planning

[3] In fact, FF combines tree search with hill climbing local search.

under uncertainty. See the *RTDP* algorithm (Real Time Dynamic Programming [4]) which solves goal MDP problems and can be seen as a special way of exploiting Bellman optimality equations. This use of simulations of the dynamic system to learn good policies is generalized by reinforcement learning techniques [57].

Iterated stochastic greedy search [12] is another interesting variant where heuristic choices are randomized and greedy searches are repeated. See [48, 5] for examples of application to planning for Earth observation satellites.

Local search

Local search [1] is a very powerful technique for the approximate solving of combinatorial optimization problems. Starting from any solution, it improves on it iteratively by searching for a better solution in the neighbourhood of the current solution: a small set of solutions that differ slightly from the current one. Although it cannot guarantee optimality, this method is generally able to produce high quality solutions quickly thanks to so-called meta-heuristics such as simulated annealing, tabu search, or evolutionary algorithms which allow a search to escape from so-called local minima: no better solution in the neighbourhood of the current solution.

It has been successfully applied to AI planning [26]. In [9], classical planners and evolutionary algorithms are combined to produce high quality plans. It is widely used to deal with scheduling problems with time and resource constraints. See [45] for an example of application to the problem of scheduling observations performed by an agile satellite.

Constraint-based approaches

The SAT and CSP frameworks (Boolean SATisfiability [10] and Constraint Satisfaction Problem [54]) are widely used to model and solve problems where one searches for assignments to a given set of variables that satisfy a given set of constraints and optimize a given criterion. To model AI planning problems, we can associate one SAT/CSP variable with each state or action variable at each step. However, the difficulty is that the number of steps in a plan, and thus the number of SAT/CSP variables, is unknown.

This is why SAT and CSP techniques have been first used to solve planning problems over a given number of steps [38, 64]. One can start with only one step and increment the number of steps each time a plan has not been found, until a plan is finally found.

In the CNT framework (Constraint Network on Timelines [67]), this unknown number of steps is taken into account inside the constraint-based model via the use of so-called horizon variables. See [49, 50] for optimal and anytime associated algorithms.

In [69] an alternative constraint-based formulation is proposed with variables associated with each possible action, present or not in the plan.

These constraint-based approaches are not limited to AI planning problems. They can be used for planning under uncertainty. See [51, 66] for two approaches applicable to the logical MDP framework.

Applications

In this section we show some selected examples of plan or policy synthesis problems we have had to deal with in the aerospace domain.

Search and rescue mission with an unmanned helicopter

For some years, Onera has been using the ReSSAC platform (see figure 3) for studying, developing, experimenting, and demonstrating the autonomous capabilities of an unmanned helicopter [22]. In such a setting, Onera researchers considered a mission of search and rescue of a person in a given area.

Figure 3 - An Onera ReSSAC unmanned helicopter

After taking off from its base and reaching the search area, the helicopter takes, at high altitude, a wide picture of this area and extracts possible landing sub-areas. Before landing in any of these sub-areas, it must explore it at lower altitude in order to be sure that landing is safe. After landing in any sub-area, the searched person reaches the helicopter, which takes off to come back to its base.

The mission goal is to come back to the base with the searched person. Fuel is limited. For any sub-area, there is uncertainty about the fuel consumed in its exploration and about the possibility of landing safely in it. The problem is to determine in which order sub-areas are visited.

Because of uncertainties, producing a plan off-line to be executed by the helicopter is not a valid approach. A policy has to be produced either off-line from the initial state, or on-line from the current state.
The problem has been modeled in the MDP framework. State variables include discrete Boolean variables pointing out whether or not a given area has already been explored and a continuous variable representing the current level of fuel. Action variables include a discrete variable representing the next sub-area to be visited. Transition probabilities are assumed to be available. There is no reward except when the helicopter comes back to its base with the searched person. All state variables are observable, but some of them are continuous. The result is thus a hybrid MDP [32].

To solve it, a hybrid version of the RTDP algorithm (Real Time Dynamic Programming [4]), called HRTDP for Hybrid RTDP [58], has been developed. HRTDP works as RTDP does, using greedy search, sampling, and learning, except that value functions which associate a value with each discrete-continuous state are approximated using regressors, and policies which associate an action with each discrete-continuous state are approximated using classifiers.[4]

We are currently working on more complex missions involving target recognition, identification, and tracking by an unmanned helicopter, for which we are making use of POMDP techniques [15].

Planning airport ground movements

At airports, aircraft must move safely from their landing runway to their assigned gate and, in the opposite direction, from their gate to their assigned runway.

To assist airport controllers, safe ground movement plans can be automatically built, taking into account a given set of flights over a given temporal horizon ahead.

To build such plans, the airport (see figure 4) is modelled as an oriented weighted graph where vertices represent runway access points, gates, or taxiway intersections, arcs represent taxiways, and weights represent taxiway lengths. In the proposed approach [46], flight movements are planned flight after flight, according to their starting time order. For each flight, a movement plan is built, taking into account the plans built for the previous flights. For each flight, the problem is to find a shortest path in the graph in terms of time, taking into account time separation constraints between aircraft at each vertex of the graph. An algorithm is used to solve it optimally. The result is a path in the graph, with a precise time associated with each vertex in the path.

These plans are too rigid and do not take into account the uncertainty about aircraft arrival and departure times and about aircraft ground speed. To overcome such a difficulty, in a second version of the algorithm, precise times associated with each flight and each vertex are replaced by time intervals. The resulting plan is flexible and remains valid as long as these time intervals are adhered to by the aircraft.

Management of an autonomous Earth surveillance and observation satellite

For some years, Onera, CNES, and LAAS-CNRS have been involved in a joint project called AGATA [16] which aims at developing techniques for improving spacecraft autonomy. A target mission in this project was a fictitious mission, called HotSpot, using a constellation of small satellites for surveillance and observation of hotspots (forest fires or volcanic eruptions) at the Earth's surface [48] (see figure 5).

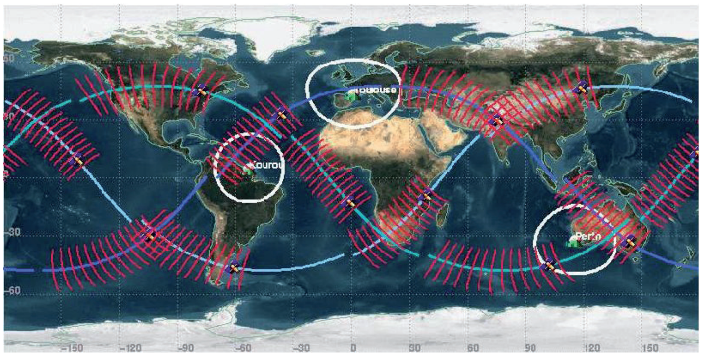

Figure 5 - Track on the ground of the HotSpot detection instrument (12 satellite constellation) within a 25 minute period

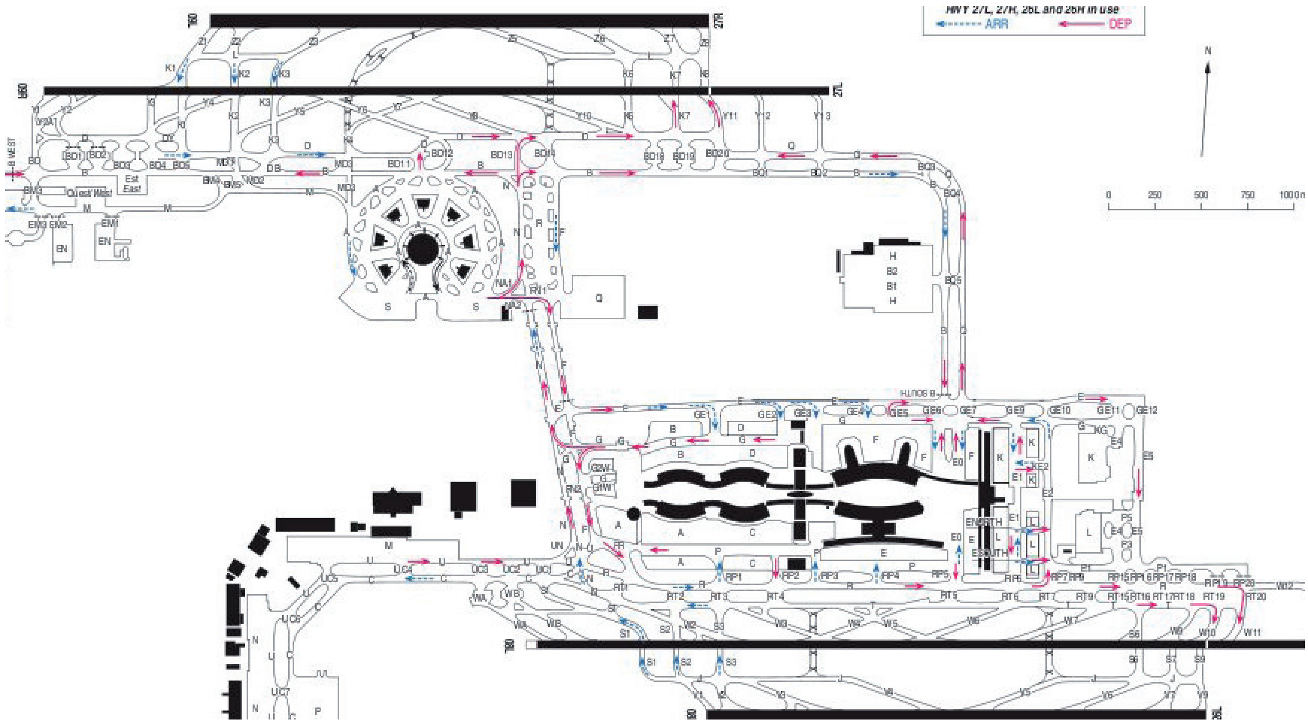

Figure 4 - A map of the Roissy Charles de Gaulle airport

[4] A regressor allows a function to be approximated. When this function takes discrete values, one speaks of classifier.

Each satellite is assumed to be equipped with a large aperture detection instrument, able to detect hotspots at the Earth surface. In the event of detection an alarm is sent to the ground via relay geostationary satellites. Each satellite is also equipped with a small aperture observation instrument, able to observe areas where hotspots have been detected or of any other areas whose observation is required by the ground mission center. Observation data is recorded on board and downloaded when the satellite is within a visibility window of a ground reception station. Decisions must be made on board on which areas to be observed, which data to be downloaded, and when downloads occur (when selected, observations occur at specific times with no temporal flexibility).

In this problem, uncertainty is due to the possible presence of hotspots. However, we do not have at our disposal any model of this uncertainty. This is why we adopted a planning/replanning approach (see § "Control synthesis modes"). Each observation and download plan is built over a given temporal horizon ahead, takes into account the known observation requests, and ignores the possible future requests that might follow hotspot detection. In case of detection of any unexpected event, a new plan is built.

To implement such an approach, we developed a generic reactive/deliberative control architecture [44] where a reactive module receives information from the environment, triggers a deliberative module with all the necessary information (starting state, requests, temporal horizon), and makes final decisions, and where the deliberative module performs anytime planning [72] and sends plans to the reactive module each time a better plan is found.

Because plans must be produced quickly, we developed an iterated stochastic greedy search. Each greedy search is performed chronologically from the starting state and produces a candidate plan. At each step, the algorithm makes a heuristic choice and checks that all the physical constraints are met. Observations and data downloads which can be performed in parallel are taken into account, as well as energy and memory profiles. Heuristic choices are randomized to explore plans in a neighbourhood around a reference plan (the plan that is produced by strictly following heuristics).

Autonomous decision about data downloading

Onera has been studying the problem of data downloading for a CNES electromagnetic surveillance mission using a constellation of satellites (see figure 6). In this mission, ground electromagnetic sources are tracked by satellites, data is recorded on board and then downloaded to ground reception centers [65].

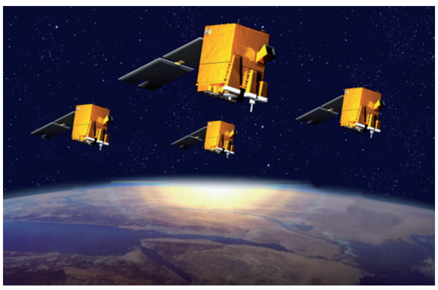

Figure 6 - The Elisa satellite constellation designed as a technological demonstration of electromagnetic surveillance capabilities from space

The main difficulty in this problem is that the volume of data that results from the tracking of a ground area is uncertain and that the variance of the probability distribution is very large. In such conditions, building data downloading plans off-line on the ground, which is how this is usually done, may be problematic. If maximum volumes are taken into account then downloading windows may be underused due to actual volumes being less than their maximum value. If mean volumes are taken into account then some downloads may be impossible due to actual volumes being greater than their mean value. In this problem, it is assumed that, for each ground area, a probability distribution on the volume of data generated by its tracking is available. In such conditions, if the tracking plan is known, an MDP model of the data downloading problem can be built. Solving it would produce a policy which would say which data is to be downloaded as a function of current time and memory state (data currently present in memory). However, the fact that the resulting MDP is a hybrid MDP [32] with a huge number of continuous variables (volume of each data in memory) has prevented us, at least for the moment, from following this approach.

More pragmatically we adopted a planning/replanning approach, close to the one used to solve the previous HotSpot problem (see the previous subsection). Each plan is built over a given sequence of downloading windows ahead and takes into account the known volumes for the data already in memory and the mean volumes for the others. Each time the tracking of a ground area ends and the generated volume is known, a new plan is built. Plans are built greedily by inserting data downloads one after the other. At each step, a download of the highest priority and, in the case of equality, of the highest ratio between its value and its duration is selected and inserted in the plan at the earliest possible moment (classical heuristics used to solve knapsack problems [39]).

Simulations show the superiority in terms of actual downloads of online on-board planning/replanning compared to off-line planning on the ground.

Challenges

Algorithmic efficiency

Algorithmic efficiency is the key issue for dealing with plan or policy synthesis problems. Most of the problems we address are not polynomial, but NP-hard or Pspace-hard according to the complexity theory in computer science [25]. This means that the worst-case time complexity of any known optimal algorithm grows at least exponentially with problem size (what is usually referred to as the combinatorial explosion) and that there is no serious hope of discovering polynomial algorithms. Thus, if the combinatorial explosion is unavoidable, the priority becomes to delay it as far as possible.

This is the role of many of the techniques we are working on, as a large number of other researchers are, such as efficient data structures, intelligent search strategies, intelligent sampling, high quality heuristics, constraint propagation and bound computing, explanation and learning, decomposition, symmetry breaking, incremental local moves, portfolios of algorithms, and the efficient use of multi-core processor architectures.

Generic vs. specific algorithms

In fact, in most of the applications we have had to deal with we did not use generic algorithms but developed specific ones, tuned for solving the specific problem at hand. The two main reasons for that are that (i) generic frameworks and algorithms are often unable to handle specific features of the problem and (ii) generic algorithms do not take into account problem specificities and are thus often too inefficient. However, this approach is very consuming in terms of engineer working time. Moreover, any small change in the problem definition may compel engineers to revisit the whole algorithm.

As a consequence, one of the challenges we have to face is the design of really generic modeling frameworks and of associated efficient generic algorithms, for at least some important problem classes to be identified. These algorithms should be tunable as much as possible as a function of the problem at hand. If we succeed then engineers could limit their work to problem analysis and modeling and to algorithm tuning.

Constraints and criteria

User requirements on the controlled system are usually of the form of constraints to be satisfied or of criteria to be optimized on all the possible system trajectories. However, some modeling frameworks such as temporal logics, classical AI planning, or logical MDP focus on constraint satisfaction, whereas other frameworks such as classical or goal MDP focus on criterion optimization. It would be very interesting to build a more general framework where various kinds of constraints and criteria on trajectories could together be represented and handled, in order to be able, for example, to synthesize safe optimal controllers.

Discrete and continuous variables

In most of the work on the problem of plan or policy synthesis for the high-level control of dynamic systems, time, state, and action variables are assumed to have discrete and finite domains of values. On the other hand, for work in the domain of continuous automatic control, it is continuous, time, state, and command variables that are considered. A challenge would be to put up a bridge between the discrete and continuous worlds in order to address problems of control of hybrid systems that can only be modeled using discrete/continuous time, state, and command variables.

Centralized and decentralized control

In this article, we have limited ourselves to problems where the control is centralized: whatever its dimension is, the physical system is controlled by a unique controller which receives all the observations and sends all the commands. However, in many situations, distributed control is either mandatory or desirable. This is the case when a fleet of vehicles (aircraft, spacecraft, ground robots, ground stations …) needs to be controlled in spite of non-permanent inter-vehicle communications. In this case, local decisions must be made by each vehicle with only a local view of the system. This kind of problem has already been formalized, using the Dec-MDP framework (Decentralized Markov Decision Processes [7]), where each agent has a local view of the system state and can only make local decisions, or the DCSP framework (Distributed Constraint Satisfaction Problem [70]), where decision variables are distributed among agents. Nevertheless, a lot of work remains to be done in this domain in terms of relevant modeling frameworks and efficient algorithms.

Human beings in the control loop

Finally, the presence of human beings who want to have the best view of the system state, want to control the system at the highest level, and want to be able to make their own decisions at any moment, is another challenge. Indeed, while it is sensible to assume that we have at our disposal models of the dynamics of artificial physical systems, this is no longer the case with human beings who may intervene as they wish, within the limits of the man-machine interaction system. See [62] in this issue of Aerospace Lab ■

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Scene Understanding from Aerospace Sensors: What can be Expected?

Automated scene understanding or interpretation is a fundamental problem of computer vision. Its goal is to compute a formal description of the content and events that can be observed in images or videos and distribute it to artificial or human agents for further exploitation or storage. Over the last decade, tremendous progress has been made in the design of algorithms able to analyze images taken under standard viewing conditions. Several of them, e.g., face detection, are already used daily on consumer products. In contrast, the aerospace context has been confined to professional or military applications for a long time, due to its strategic stakes and to the high cost of data production. However, images and videos taken from sensors embedded in airborne or spatial platforms are now being made publicly available, thanks to easily deployable UAVs and web based access data repositories. This article examines the state of the art of automated scene interpretation from aerospace sensors. It will examine how the general techniques of object detection and recognition can be applied to this specific context, as well as what their limitations are and what kind of extensions are possible. The interpretation will be focused on the analysis of movable objects such as vehicles, airplanes and persons. Results will be illustrated with past and ongoing projects.

Introduction

What is scene understanding?

Scene understanding or interpretation is a traditional field of computer vision. It consists of designing algorithms able to associate data produced by image sensors with a formal informative description enunciated in a shared language. The target description is defined by the context of use and it is often reduced in practice to detecting, characterizing and locating in space and time the entities and events of interest.

The role of scene understanding in a global system is to generate a formal description that can be communicated, stored or enhanced by various agents, either artificial or human and is therefore not the ultimate output of a processing chain. This also means that the requirements for the interpretation result quality depend on the purpose that it will be exploited for.

Humans have no difficulty in describing what they see in an image or in a video and in reasoning about the cause and consequences of the observed phenomena. It is a platitude to state that this easiness is not shared by artificial devices such as computers. The expression “semantic gap” has been coined to refer to this problem and expresses the fact that the information encoded in computers does not spontaneously match the inner structure of sense-data.

One possible explanation of this difficulty lies in the complexity of the function relating data to description: the input space is a point in a vector space of high dimension – the number of pixels – that maps to an often hybrid space mixing continuous and discrete representations. The data distribution is therefore very sparse in its representational space, with no obvious regularities that can be captured in a simple form. Physical models may help by introducing some constraints, but are not sufficiently accurate or general to account for all phenomena occurring in real situations.

What is special with the aerospace context?

By the aerospace context, we mean in this article two families of data: large still images from remote sensing satellites and images or videos from airborne platforms. Aerospace data acquisition for scene understanding is interesting for several reasons: it can be discreet and non-intrusive; it allows wide area views; it can provide information from isolated regions; it can produce various viewing conditions to remove ambiguities. One of the first applications has been intelligence through image analysis: aerospace sensors for scene understanding have been deployed since the beginning of photography, for instance for tactical information gathering on the battlefield using aerostats. Similar applications include surveillance or targeting. Information acquisition for search and rescue purposes after a natural disaster are currently being studied. Environment monitoring is a traditional application of remote sensing data. The availability of large quantities of image and video data drives the need for smart archiving and retrieving schemes and the construction of semantic keys describing their content.

Sense-data in the aerospace context is specific in several respects. It is usually of high dimensions – it is not unusual to handle giga-pixel images in modern remote sensing data; it is often acquired under non-intuitive viewing conditions (nadir or oblique point of view); it may be produced by unusual sensors (radar, infrared, laser, hyper-spectral, etc.). However it often comes with extra metadata, typically describing the date, the viewing conditions within a given error range, or the weather conditions. Other sources of knowledge, such as maps or other similar data with informative ground truth, can also be exploited to introduce informative priors.

Although image and video data is now made easily available thanks to huge repositories (Google, Flickr, Getty, etc.) aerospace data is still scarce. A first explanation is that the aerospace context has always been strategic for governments and is therefore carefully controlled. A second explanation lies in the cost of producing good quality aerial or remote sensing data, limiting its use to professional applications. This situation is becoming less true nowadays: flight platforms with embedded sensors can be deployed more easily, high resolution remote sensing and "bird's eye view" images are readily available on any computer connected to the Internet. This new trend was recognized in the recent and first workshop on aerial video processing (http://manufacture.nimte.ac.cn/vision/wavp/) addressing the need for automatic tools for aerospace image data analysis.

The goal of this article is to provide a broad view of the state of the art of automatic scene understanding from aerospace image and video data. The next section will give a short description of the current techniques used in modern automatic scene understanding with specific emphasis on movable objects. The further two sections will concentrate on the problems of detecting and characterizing the entities and events of interest. Outputs of environment reconstruction and data registration will be assumed and are presented in a companion article of this issue [99], or can be found in other reviews [59]. The following section will give some insight on more complex settings. The last section will give some clues in regard to the state of the art performances, in terms of accuracy and processing time. The conclusion will state a few forthcoming challenges.

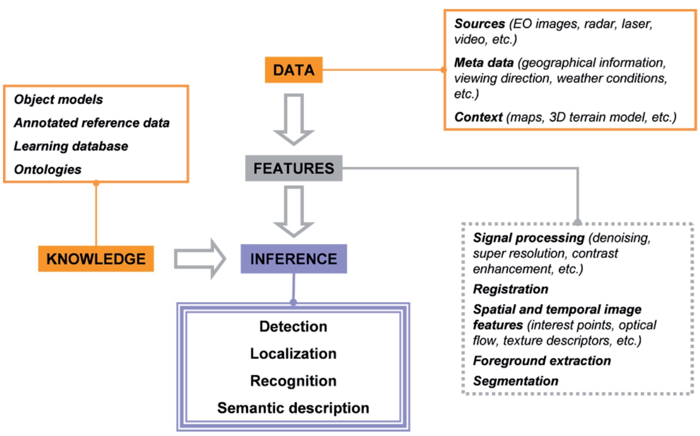


Figure 1 - General structure of processing chains for scene understanding from aerospace image sensor

Techniques for automated scene understanding

The main problem facing automatic scene understanding is a complexity issue: how to map a high dimensional sparse sense data space to a hybrid discrete and continuous interpretation. The general paradigm applied to solving this problem is to project the input data into an intermediate representation, commonly called a feature space, and then making knowledge based inferences (localization, recognition, description, etc.) from this space (figure 1).

Feature extraction + inference

The objective of such a feature space is manifold: it is expected to reduce the dimension, to make computations easier, to normalize heterogeneous data in a common framework, to reveal information, to remove noise and biases and to be invariant to known nuisance while staying discriminative in the inference space. It therefore plays a very critical role in the processing chain.

Driven by industrial vision applications, the first type of features that have been used were inspired by geometric considerations [78]. They mainly consist of simple elements, such as corners, segments or lines and are rather easy to extract. However, their lack of robustness to various illumination conditions and their limited expressive power have restricted their use in real operations for interpretation purposes.

The next generation of feature spaces were built on geometric or spatio-temporal landmarks [75][61], but were augmented with local image descriptors to better characterize the image and to introduce textural patterns in the intermediate representation [76]. This kind of feature space has higher dimensions compared with a pure geometrically based description, but is still far more compact than the original data.

Features are local, i.e., they only characterize a small part of the original data. Scene understanding is global, even if the interpretation contains local information (location of entities). Before going into an inferential step, there is a need to gather and encapsulate the local features in formal objects based on some sort of geometric extension: regions, bounding boxes, spatio-temporal tubes, 3D structure, collection of patches, etc. Many schemes have been proposed [62] [53] and evaluated for several types of data.

The next issue, given this simplified or intermediate feature space, is to produce reliable inferences to generate the interpretation in a given language or set of hypotheses. Ideally, features would be considered as direct indexes to the interpretation space. Unfortunately, it does not happen this way: features are still noisy, not sufficiently discriminative and still too complex. The inference step, i.e., the stage that actually produces the interpretation, also requires rather sophisticated processes. A popular solution is to use a learning algorithm to build the interpretation function from a set of reference data and handle the various levels of uncertainty or noise left in the feature data (see box 1).

Coupling features, models, reference data and inference

In practice, segmenting the processing chain into two uncorrelated steps – feature extraction and inference – is conceptually appealing but not optimal. Good features depend on what kind of information they carry, the quality of the information being measured by the targeted interpretation problem. Indeed, the huge volume of research studies shows that there is no consensus on universal features, or on a general inference engine. The feature extraction and inference stages are in general designed jointly and purposely.

A first common practice making the two stages cooperate is the classical task of feature selection or construction. In this scheme, the goal of the first step is to provide an over complete set of informative features that will be selected or combined by the inference step according to an error criterion. In machine learning, the well-studied boosting family is a powerful instantiation of an integrated feature extraction + inference design (see box 1).

The inference step is heavily dependent on the nature of the reference data and on the available models. Objects represented by CAD models, collections of images, logical descriptions or deformable templates are not exploited in the same way. They constrain both the type of features that can be profitably extracted and the structure of the inference algorithm.

Prior or contextual data is often available in aerospace data: maps with various levels of semantic information or geo-referencing, viewing and weather conditions, 3D environments, knowledge representations such as ontologies, etc. They contain useful information that can be exploited to reduce the number of hypotheses to handle or map the features onto a cleaner and lower dimensional space. Though using extra sources of knowledge is appealing, there is no systematic way to introduce them into the processing chain. They can also bring their own type of noise and make data interpretation less robust if too much trust is given to their value.

Scene understanding processing chains can therefore be very complex. Though as a first approximation they all follow the same basic feature extraction and inference scheme, the research literature proposes many variations around it. One of the reasons for this high volume of research is the current performance level: with a few notable exceptions, it has difficulties to be really operational. Although improving and addressing new issues each year, it is hard to claim that automated scene understanding is a solved problem.

Box 1 - Machine learning for scene understanding

Object models have been restricted for a long time to physical models such as CAD polyhedrons with optical description of materials, illumination and viewing conditions. Physical modeling is limited – it cannot predict all of the observed phenomena in a simple form – and relies on knowledge of parameters that are hidden most of the time and must be inferred from the data or from reasonable hypotheses.

Machine learning offers a series of empirical techniques able to produce models from sample data with minimal assumptions. Its cornerstone concept is generalization, i.e., the capacity of producing meaningful inferences from unseen data. Theoretical results ensure that the empirically generated models have good properties (convergence, bounded generalization errors).

The last decade has seen statistical machine learning techniques invading the area of computer vision, especially the field of object recognition. A conjunction of events can explain this fact: new powerful learning techniques, increase in computer power, easily available digital data, stagnation in performances in pure geometric approaches and a new generation of researchers. Almost all modern and efficient scene understanding algorithms include in their processing chain a module whose parameters have been estimated by machine learning.

What is machine learning?

A collection of algorithms able to mimic a function from sample empirical data. We talk of classification when the output is discrete and of regression when it is continuous.

What are the main achievements?

Powerful algorithms and software toolboxes relying on solid theoretical grounds can now be exploited quite easily, without too much theoretical knowledge.

What are the main algorithms used in scene understanding?

Large margin (Support Vector Machines), neural networks and ensemble classifiers (boosting, bagging, random forest) for classification [17] , Kernelized Gaussian processes for regression [95] . Other more classical techniques such as Principal Component Analysis and Discriminant Analysis may produce acceptable results in low dimensional problems.

What are the limitations?

Data must be representative. No guarantee that the output will be meaningful on outliers or biased data, although several techniques are currently being developed to handle this problem.
And what are they in the aerospace context? The availability of data mainly limits the use of machine learning techniques to on-line approaches, or generic problems (person and vehicles detection). Another limitation is the processing time required by several approaches.

The following sections will present in more details the achievements to date and the specificities of several scene understanding problems. The first logical step of scene understanding will be described first: detecting the presence of entities of interest and locating them. However, as will be made clear, the detection step may require more specific object descriptions, implying that recognition is often logically antecedent to detection: bottom-up (detection) and top-down (characterization) processes are intimately linked in a global interpretation loop. Detected entities have some qualities and therefore carry pieces of information that must be revealed: how to extract this information and how to communicate it will then be presented. The aerospace context offers unconventional ways to acquire sense-data that will finally be described.

Object detection and localization

Detection is the first logical objective of image data interpretation, since it reveals the presence of entities of interest. Aerospace sensors are used in multiple situations and produce data of various types and qualities. Non-conventional sensors can make use of the specificities of the aerospace sense-data acquisition mode (see box 2). Detection algorithms depend mainly on the apparent object size: entities observed as fewer than ten pixels are not handled in the same way as entities spanning thousands. Moving objects are also a special case. The sections below will present a broad view of these issues.

Small objects

In many automatic surveillance activities, objects in the sensor range appear small or even unresolved. Early detection of such objects is fundamental, in order to perform higher level recognition tasks by pointing a better resolved sensor onto them. The scope of this section is detection from an image or a sequence of images. An example of such an application considered at Onera is the detection of objects on a runway (DROP project): in such a context, a 2cm part fallen on the runway appears as less than the size of a pixel on the image because of the wide field to be covered. When one considers small objects, very few features can be used from the object itself; typically, in many application contexts, only its position and intensity are available. Conversely, image backgrounds may have a huge variety of appearances; being non-stationary temporally and spatially, this variation emphasizes adaptive processing, where background behavior on a current image is deduced from previous images, or from spatial neighbors [73].

We have developed different methods based on building background statistics against which a pixel or a group of pixels is tested. The first one [29] considers a "detection by rejection" method. In this context, we have proposed several statistical approaches to correctly estimate a model of the environment. In particular, we have proposed the use of a mixture of densities, to guarantee a good estimation in case of background transition. An example of such processing is given in figure 2, on a SAR image. A second trend of research consists in building robust means for background pixels, by fetching pixels in a much wider area than the usual local windows and weighting them, using a patch similarity measure like the Buades "Non-Local means" [24]. The approach, denoted detection by NL-means (D-NLM), proved to be very efficient on non-stationary structured backgrounds, such as clouds [39].

When the object is moving w.r.t. the background, one can take advantage of image sequences, instead of single images. In such cases, a very simple cascade of motion compensation, threshold and short-term temporal association yields very good performances, provided that the background motion is described by simple parametric models. We showed that a particular spatio-temporal extension of D-NLM deals very efficiently with the alternative complex motion context, requiring only rough motion compensation [39].

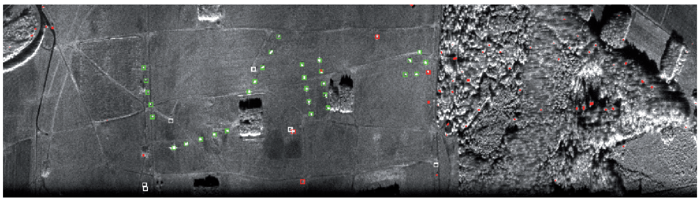


Figure 2 - Detection result on a SAR image.
Green squares mark good detection, red squares indicate false alarms.
(better viewed by magnification on screen)

Extended objects

When the resolution is sufficiently high, object appearance is associated with a region typically of the size of several hundreds to several thousands of pixels in an aerospace context. This means than the object appearance contains textural information, but this intermediate size also dismisses approaches relying on fine details.

The algorithms for object detection conform to a structure in three successive stages sharing the load of calculation:

- Saliency detection. This computes a low-cost list or regions potentially containing an object, with high level of confidence. It may use "generic" object models for persons or vehicles.
- Detection by recognition. This computes a confidence measure or a likelihood for each region, given the object models. It possibly provides a segmentation mask of the target to improve localization.
- Spatial filtering. This ensures that the detected objects have a consistent spatial distribution. This step eliminates obvious artifacts, by using simple and inexpensive rejection mechanisms.

The first step requires fast algorithms: stationary filter banks [26] [70], cascades [60] [111], coarse to fine schemes [11] , etc. It often greatly benefits from a parallel implementation (GP-GPU). The challenge is to identify salient structures from a background that is also structured. The algorithms are based on features able to discriminate textures or patterns characteristic of artifacts from those corresponding to natural elements. When the ground resolution is unknown, it is usually necessary to perform multi-scale analysis (pyramid filters, wavelets, scale space, etc.) to scan the potential size of the observed objects (figure 3). These techniques are in general increasing the number of false alarms to be filtered in the subsequent phase. In the case of urban settings, containing many artifacts (buildings, infrastructure), the exploitation of registered maps and the knowledge of image resolution can be a great help to constrain the decisions.

Though the first step is to be considered purely bottom-up, the second step (detection by recognition) implements a top-down process. It uses more sophisticated features to characterize the hypothetical object, or to reject it. It often contains an extra class for background identification, or a rejection scheme able to state that a given instance is out of the scope of the hypothesized objects. The models used to compute the likelihood are similar to those developed for object classification or categorization: configuration of parts [35], accumulation scheme [38] [63], histograms of local features[62] [90].

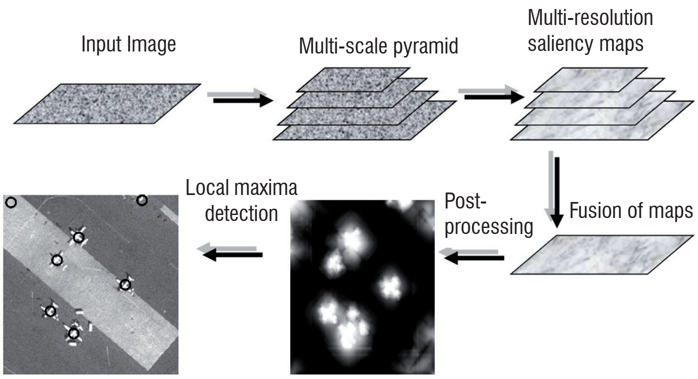


Figure 3 - Typical chain for multi-scale saliency detection. The saliency maps are built using a combination of contrast detectors (Gabor filters) and local scale estimation [26].

Moving objects

Detecting and localizing moving objects in the scene is fundamental to many higher-level interpretation processes, both in the aerospace and the security context. Examples include detecting other airplanes while airborne, maritime surveillance, pursuit of land vehicles from the air, as well as visual surveillance where either individuals or faces must be detected and localized over time.

The detection of moving objects can be divided roughly into two phases: acquisition, which reveals the presence of an object of interest and pursuit, which filters its location over time.

Many existing acquisition approaches rely on change detection and inter-frame correspondence, i.e., comparing the incoming image with a reference, which could range from a single image to a model obtained from data. However, the underlying assumption of this approach is that the sensor is fixed in location, which severely limits its applicability in the aerospace context. Image registration techniques can compensate for the apparent motion between frames (see article [99] in this issue), but cannot get rid of the parallax phenomenon, i.e., the apparent motion due to tri-dimensional structures in the scene. Furthermore, objects may enter and leave the observed area because of the moving platform, breaking the time continuity of its appearance. The literature solves these problems in two ways.

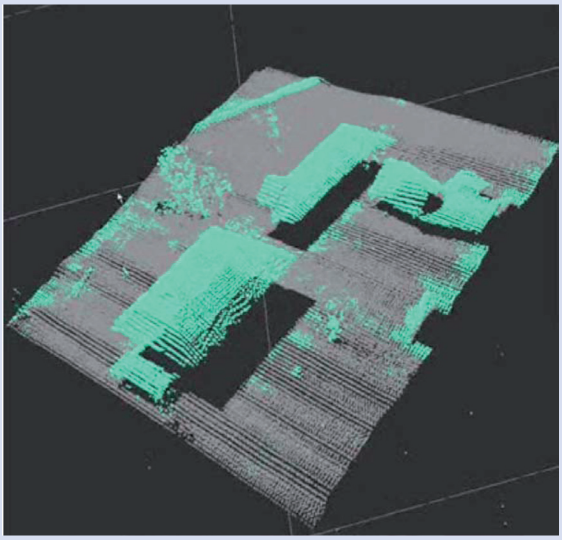
The first idea is to mix the two phases of object acquisition and pursuit. Object features are learned either offline or online to allow re-detection and localization during runtime. Approaches involving offline learning are applicable if the appearance of the objects of interest does not change overtime and if sufficient training data is available. However, in order to handle possible variations of the objects of interest, adaptive techniques (i.e., online learning) are required to incrementally update their representation. Multiple variations around this scheme have been proposed, especially in the case of single object tracking ([40]). The detection and tracking of multiple objects from moving sensors, exploiting machine learning techniques, have been studied more recently [22]. These approaches rely on a good appearance characterization and are therefore more suitable to rather large extended objects.

A second idea is to filter out the residual noise after motion compensation, either by introducing object motion models and/or contextual information [9]. These techniques are applicable to smaller size objects. Longer time scale filters allow a more global analysis on blocks of data [113], or post processing on elementary tracks [71]. We have proposed to introduce a light learning step to take into account local context estimation in the inference [41] to specialize the processing chain under various viewing conditions and scene contents easily. Figure 4 shows several detection results on very different styles of image content.

Figure 4 - Results of moving object detection using local context estimation on videos with different viewing conditions [41].

Box 2 - 3D object recognition based on laser data

Ladar (Laser Detection And Ranging) is a powerful technology that provides direct access to three-dimensional information. Originally limited to macroscopic meteorological and atmospheric research, recent technical developments of ladar (miniaturization, lower cost of ownership and maintenance, eye-safe operation, performance) has led to considerable diversification of potential application including 3D object recognition.
Recent competitions on this topic (see, for instance, SHREC, http://www.aimatshape.net/event/SHREC) have encouraged the development of efficient 3D recognition algorithms. The following approach (representation / feature extraction / database inspection / model matching) is quite generic and representative of most algorithms from the state of art [16][23][68][87][86].



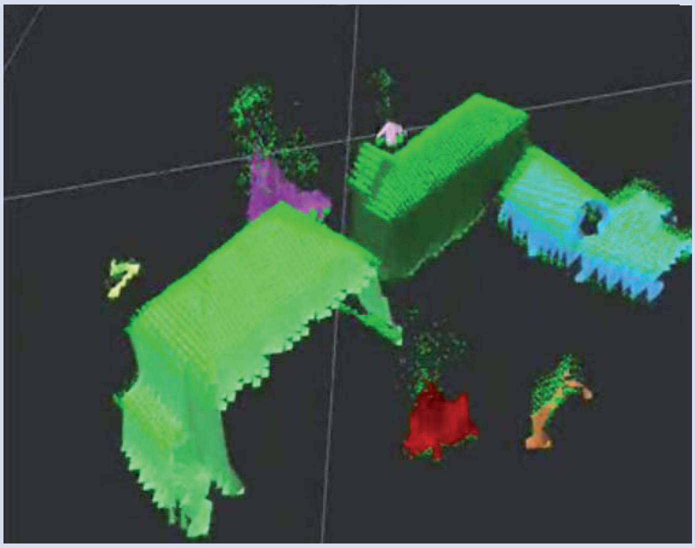


Figure B2-01 - 3D laser acquired by the Onera UAV Ressac. Detected clusters of 3D points are shown in green (left picture) and allow the object extraction phase (right picture).

Ongoing research is currently focused on the following topics:

- The model representation: It should present simultaneously a highly discriminative power and a limited complexity.
- The constitution of the database. Its structure determines the speed and performance of any algorithm for automatic and real time recognition.
- The efficient and robust extraction of characteristic features of any object, even in the presence of noise or clutter.
- Effective recognition (matching) from the set of characteristic elements that has been introduced previously into the database.

Current developments are aimed at improving and embedding 3D recognition algorithms for the exploitation of data acquired by Onera UAVs. (see figure B2-01).

Content description

This part will concentrate on what can be inferred once the entities of interest have been detected in space and time. It will concentrate on three types of interpretation: 3D object classification, action and behavior description and it will present a focus on the prospective research area of high level semantics.

Object recognition

Object recognition is a rather imprecise expression referring to various types of discrete decisions from image data. In this section, we will focus on two types of functions: classification according to a given list of hypotheses and re-identification based on a similarity measure. The typical targets of choice are vehicles, which have generated many studies driven by traffic surveillance, battle field situational awareness or intelligence applications. Person recognition in an aerial context has been less investigated [87], but the increase in video resolution is likely to stimulate new approaches. To face the challenging conditions of the aerospace context, various approaches have been proposed. We will focus on the solutions that can be deployed in practical situations.

Classification, i.e., the choice of a hypothesis from a set of possibilities – category, object model, brand, aspect, etc. –can be used as a final interpretation or as a means to filter out outliers using a rejection mechanism. It is a critical function in image understanding and has therefore received considerable attention. In re-identification, the set of hypotheses is a list of previously observed objects and relies on a similarity measure or on a conditional likelihood: it is mainly used to associate observations at different dates between distant fields of view to increase the temporal continuity of interpretation.

Aerospace sense-data (still images or videos) can be obtained from various sources, the sole common feature of which is the fact they are located above ground, from low-flying micro-uavs to satellites. This implies a wide variety of viewing conditions: points of view are usually oblique, which leads to unusual appearances of the objects. One of the main difficulties is the 3D nature of objects and the variety of appearances that a single object can produce. Moreover, aerospace data is often noisy, due to motion blur, bad color calibration, low contrast or saturations, bad focus, etc. A second practical issue is the need for an object model that can handle all of these types of nuisance.

Three dimensional object modeling is an old problem in computer vision, and was originally studied to locate an object and estimate its position from well-defined CAD geometric models [78]. This kind of approach is limited to a specific object shape. When it comes to a more general category of objects, new types of models must be defined.

A first idea is to exploit learning-based methods and blend them with geometric models. Several approaches have been used to estimate the position of vehicles [69] [88], by learning the visual appearance from various 3D points of view and the 3D geometric relationships to produce a global model [101] or by trying to fit a complete 3D appearance model [64] [56] [45]. All of these new approaches are particularly greedy for training data, a condition not often satisfied in the aerospace context. In practice, only simple models are manageable.

In object re-identification the algorithms depend mainly on the difference of viewing conditions: same sensor or not, same point of view or not. Many of the re-identification approaches in the aerial context aimed at correcting detection gaps [44]. Several approaches also make use of learning techniques to build a similarity measure between images adapted to a given setting [83] [36]. In [42] we proposed several solutions to object re-identification exploiting 3D modeling for aspect extrapolation and self-occlusion handling. Global and sparse appearance descriptions have been evaluated in an experimental set-up aimed at urban surveillance using a camera network with oblique points of view.

Action and behavior analysis

Action recognition refers to the classification of spatio-temporal patterns over a short time interval and seldom involves more than two or three agents. Usually the set of actions that we wish to recognize is defined and action recognition is the process of determining which action class the given data belongs to. Behavior analysis, on the other hand, refers to the recognition of phenomena that are more long-term and usually involves multiple interacting agents. Often, "normal" behavior is learnt from data and any deviation from this norm can be used to detect anomalies.

Many human action recognition approaches share the same global structure, where extracted spatio-temporal features of the different actions are used to train a classifier. The difference between silhouettes several timesteps apart is used as features in [94]. In [79], an action is represented by a sequence of primitive actions and learning is accomplished on a small dataset. A bag-of-words-based approach with a hierarchy of class-specific vocabularies using neighborhoods of spatio-temporal feature points is used in [57]. In [67], view-point and style independent manifolds are learnt to improve robustness. A Hough Transform-based voting where random trees are trained to learn a mapping between feature patches and spatio-temporal action Hough space is used in [112]. The problem of selecting the most discriminant part of the data by proposing an automatic optimal cropping applicable to action recognition techniques in general is addressed in [100].

Behavior analysis also relies on machine learning, except that a global representation of normal behavior is automatically extracted from the data and "anomalous" behavior can be detected by the fact that it cannot be explained by this representation. In [19], any new query that cannot be constructed using the video segment database components is classified as abnormal. Global motion flow fields are used to determine the dominant motion patterns called "supertracks" in [48]. A global representation using spatio-temporal co-occurrence between motion vectors is proposed in [103].

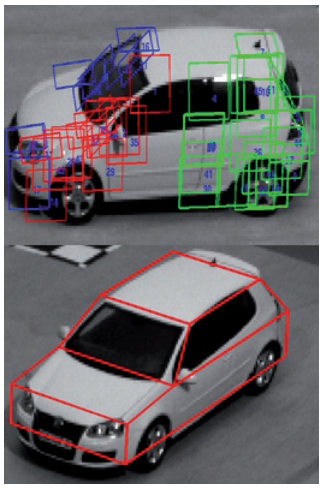


Figure 5 - Example of vehicle re-identification with various aspects [43].
On the left, images in the first column are "queries" that are to be matched with the color framed images. Green means good match, red means false match.
On the right, two kinds of models used to extrapolate aspects: sparse and global.

In [58], spatio-temporal features are extracted to be used in a coupled-HMM. Behavior analysis on crowds is also starting to receive much attention, its interest shown by the inaugural workshop on large crowds at the last ICCV [7]. For a comprehensive review on crowd analysis, see [51]. In the aerospace context, research on behavior analysis focuses on learning normal traffic patterns from tracking information, so that deviations from this norm can be detected as an anomaly [49] [21] [98] [77].

A behavior analysis problem that has been studied for many years is the long term trajectory characterization of humans, vehicles and airborne platforms, in the ultimate objective of supporting long-term reasoning; however, it is only recently that solutions are being proposed. The technology for tracking an object for a short time interval has reached a relatively mature level. However, maintaining continuous tracks over a longer duration is still a difficult problem, since occlusions, both static and dynamic, mean that the labels assigned to individual objects are not unique. Interactions between entities, for example the formation and splitting of groups, add another layer of difficulty to the problem.

A new trend for addressing this problem draws on the analysis of groups. Social force models have been proposed to explain the physical dynamics and groupings of individuals [74] and Pellegrini et al. proposed a joint estimation of tracks and groups [89]. We propose a solution based on Markov Logic Networks (MLN) [66][96]. An MLN is the application of a Markov network to first order logic and combines both logical statements and probabilities [109] into a single framework. This approach is promising, since it allows higher-level reasoning and multiple types of queries on the data structure. Figure 6 shows a typical complex situation with the formation and splitting of groups whose interpretation will benefit from such an approach. In such a situation, traditional trackers will return eight tracklets, but will be unable to infer the tracks of the three people. Applying the MLN-based solution here allows the three tracks to be recovered.

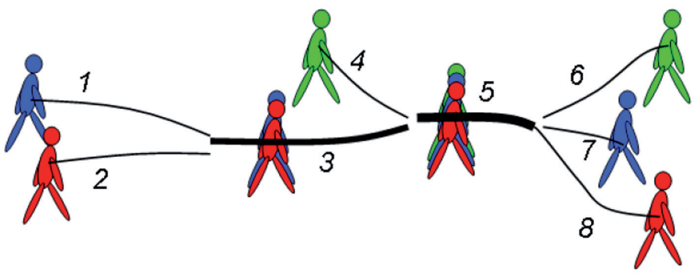


Figure 6 - Illustration of the complex behavioral patterns that can be interpreted using our Markov Logic Network approach ([66]). Tracklets 3 and 5 are tagged as groups. The resulting structured pattern allows different levels of reasoning for further interpretation.

Complex settings

The presentation above has described scene understanding issues from a single image or video stream, concentrating on the specificities of the aerospace origin of data. Acquiring images from aerospace platforms allows increased flexibility in the acquisition settings. This part discusses three of these: the exploitation of multiple points of view, of multiple sources and of multiple sensors.

Multiple points of view

Aerial sensors are embedded in moving platforms. Movement can be considered as a nuisance requiring compensation (see section on moving objects). But it can also be considered as a chance for information gathering by allowing multiple viewing conditions and therefore different ways to look at scene content.

Multiple points of view can be considered either as a redundant or as a complementary source of information. Redundancy can be used to remove noise or enhance the quality of the input signal. Interpretation performances are improved by exploitation of complementarity properties.

One of the main difficulties of vision is the management of occlusions; objects can be hidden by others and by the environment; they also occlude themselves and show to the camera only one aspect, which may be not informative for several reasons (no corresponding reference data, ambiguous appearance, or incomplete model).
The management of multiple points of view for interpretation is generally closed loop and addresses three different problems:

- Inference: what multiple view combination schemes use in order to build the final interpretation;
- Informative state modeling: how to encode and sequentially update the current information level reached;
- Control: what action or sequence of actions may improve the information state, and on what grounds.

This “active vision” approach has received a lot of attention, especially in the robotics community, since it implements a perception/action loop. The main problems addressed have been 3D environment or object reconstruction, object search in complex environment or unknown position and object recognition [97] . The problem of sensor placement and information fusion in multiple camera networks [52] [8] [104] can also be interpreted as an active vision question and will be presented in more detail in another section.

In the aerospace context, the position of an object relative to the observer, its aspect, is hard to anticipate. Each item of image data carries some information, but often not enough to discriminate between all of the hypotheses of a given set. Several studies have addressed this multiclass problem using an active recognition scheme, where the next view [30] [20] [13] [31] [32] or the observation strategy [46] [47] is optimized. Figure 7 shows an example of the influence of the number of views acquired on the recognition accuracy for a problem of vehicle classification with rather similar shapes.

Box 3 - Rich semantics perception

Object recognition achievements have considerably improved with the development of new techniques, especially the coupling of machine learning and multiple feature representations of objects. However, when the number of classes or categories to be discriminated increases, performance seems to plateau: the smallest classification error on an item of the well-studied benchmark data containing 101 categories [5] is about 30%, a performance level that cannot be considered high enough for real operational applications.

One possibility for overcoming these limitations is to increase the size of the data set and hope that learning algorithms will scale accordingly. A second idea is to consider "flat" classification as a simple instance of a more structured description language with richer semantics, where more subtle and potentially more reliable scene interpretations can be generated.

A first instantiation of this principle is simply to build a hierarchy of classes and exploit this structure, both in the algorithm design and in the output: for example, in a problem of vehicle classification, if the precise model ("Citroen C3 5 doors") cannot be issued reliably enough, a simpler higher confidence level "Hatchback" description would be preferable (figure B2-01). [108] presents a recent review of the use of hierarchies for image understanding.

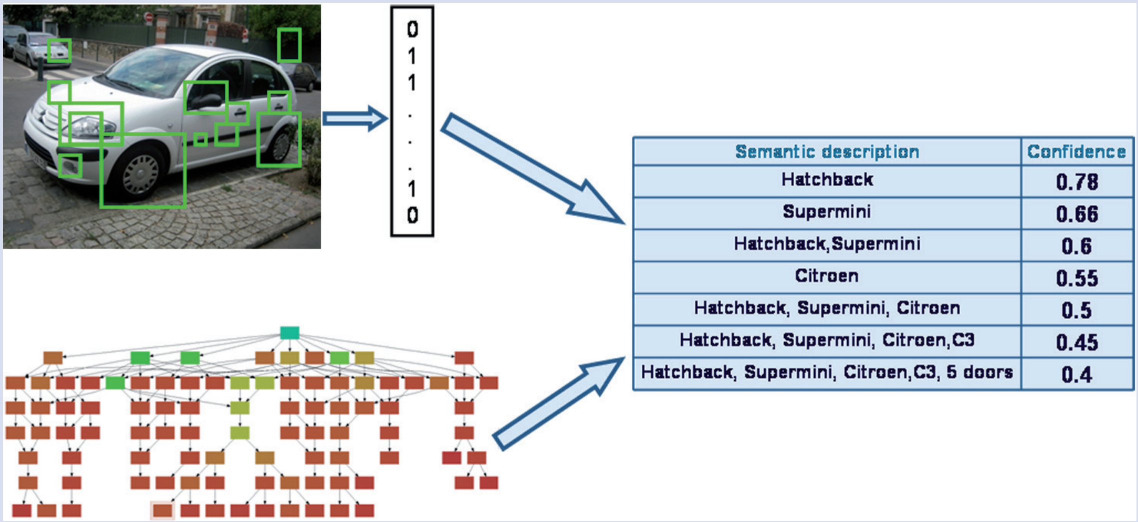


Figure B2-01 - Example of a multiple level semantic description of a vehicle. The output is a distribution of tags constrained by a hierarchy and with associated confidence. The less semantically precise it is, the more confident [107] it is.

The introduction and development of tools for richer semantics management in the description of image and video data is a rather new trend of research. It takes inspiration from various other fields, such as natural or computation linguistics, knowledge engineering, semantic web, structured data processing and multimedia database and has made concepts such as stochastic grammar [116] [93] or ontology [6] meaningful for scene understanding.

One of the key issues is the description and management of uncertainty. Indeed – this is especially true in the aerospace context – scene description is often not the ultimate output of an artificial system exploiting sense data and is likely to be exploited by other agents: since scene understanding outputs cannot be produced with infinite confidence, there is a need to provide the results in a form that contains a usable representation of uncertainty. The trade-off between confidence and complexity of description or semantic precision is one aspect of such a question.

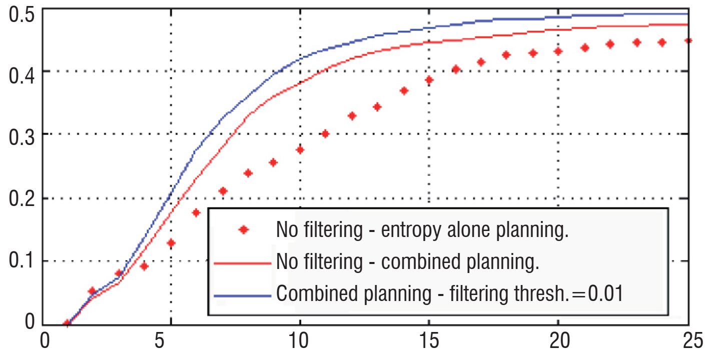


Figure 7 - One example of an active recognition problem [30]. The 8 objects to discriminate are all vehicles (left). The three view planning strategies generate various recognition rates (right).

Multiple sources

The multiplicity and variety of sensors available today that are capable of delivering complex digital information strongly encourage interest in their joint use in current or future intelligence systems. This fusion of information is a particular need in the context of a complete C4ISR chain (Communication, Command and Control, and Computers, Intelligence, Surveillance and Reconnaissance) [25] . The expected benefits are a greater capacity to analyze complex situations and robustness to the environment [18] .

Onera has been conducting research on this subject for several years. In particular, in [15] we proposed the definition of a functional architecture of SAR/optic images fusion for automatic target recognition, in a satellite or aerial context. The approach is based on the use of conventional methods of recognition, on the one hand a bottom-up method that allows us to make different assumptions on the basis of target information extracted from the images and, on the other hand, a top-down method that verifies each of these hypotheses using a matching model/image technique (see figure 8). The originality of the approach lies in the reasoning mechanisms in place. These occur mainly in the ascending phase, controlling the extraction of information by using the concepts of fusion or cooperation of sources, and, secondly, by allowing a gradual exploitation of this information

In the area of UCAV (Unmanned Combat Air Vehicle), we have developed a perception module whose aim is to increase the independence of the system by proposing fully automatic functionalities for image understanding of sensor outputs. The implemented functionalities are "automatic target detection" resulting from "fusion of the detections from 2 SAR images" and "automatic target recognition from optroelectronic (EO/IR) images".

Thanks to its stand-off acquisition, its wide field, and its all-weather capabilities, SAR imagery is particularly well suited to detecting metallic objects in a natural environment. The method of detection is based on censoring techniques, a target being regarded as an anomaly compared to its close environment (figure 9).

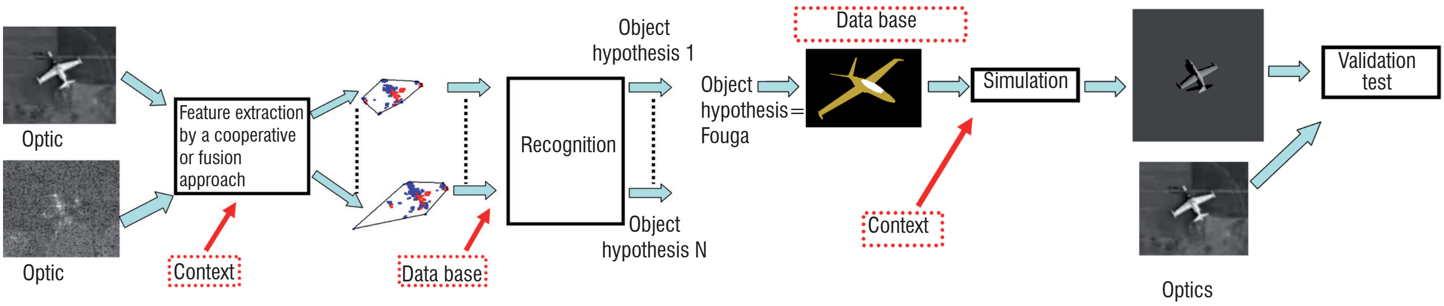


Figure 8 - Left: bottom-up process – hypothesis generation. Right: Top-down process – hypothesis verification

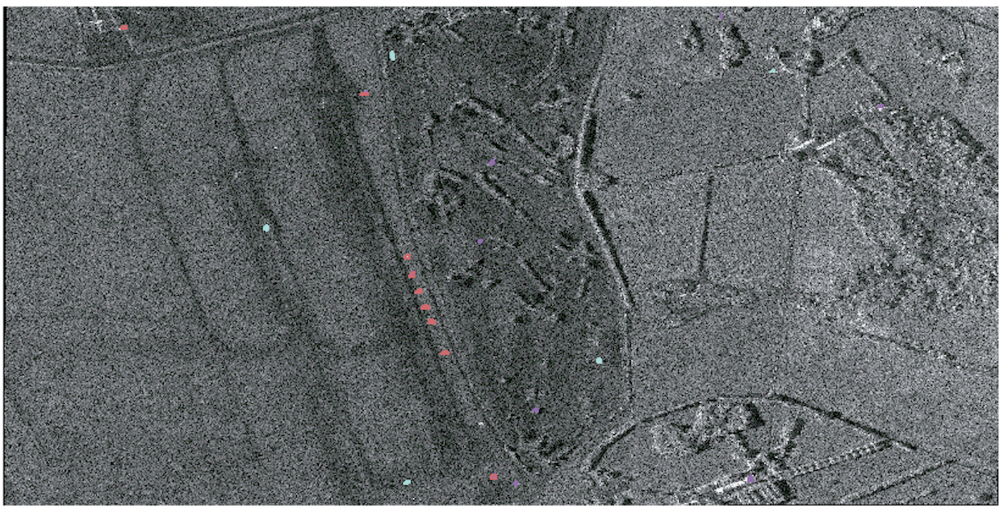


Figure 9 - SAR detection (blue: image#1 detections, purple : image#2 detections) and fusion (red)

In order to limit the amount of information coming through the data links, the result of the detection of each SAR image is transmitted as a list of points located by their geographical positions. The fusion of detections is then carried out in a decentralized scheme, producing a list of objects of interest characterized by a confidence index (plausibility).

Vehicle recognition is carried out on the basis of two triplets of high-resolution images (visible and infra-red), since the current performance of the identification process with SAR images is not sufficient to consider automation. Each triplet consists of an image acquired at nadir and two images acquired using an oblique optical axis (±45°). Recognition is based on a template matching method that uses a local planar geometric model to fit 3D models to the vehicle silhouette in the image (figure 10)[72] .

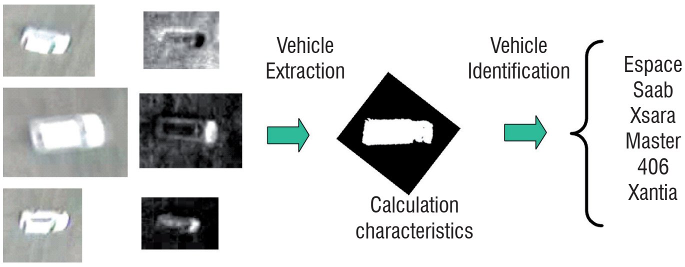


Figure 10 - Block diagram of the baseline ATR system [72].

Sensor networks

Sensor networks are often encountered in distributed systems. Their configurations range from sensors with a shared, overlapping field of view, to sensors that are non-overlapping. The primary purpose of using sensor networks is to increase the amount of information available for subsequent processing. For overlapping cameras, multiple views of the same scene can, for example, improve localization accuracy [28] [92]; for a series of non-overlapping cameras, the coverage area is increased.

One of the main difficulties in using a sensor network is to ensure correspondences amongst the cameras. On a basic level, a geometrical calibration process handles positional correspondences [105] [115] . However, for an extended network, the configuration of the cameras is also required for handling "sensor handoff" [28]. This addresses the following question: when an object leaves the field of view of one camera, which are the possible cameras with which the object can be viewed next? In addition, since the viewing conditions and the response of each camera can be different, the same object viewed by different cameras can be different. In order to associate objects across different cameras, a color calibration process is also required [10] [50] [54] [92].

Perhaps one of the most common deployments of sensor networks is in public transport networks, e.g., the use of surveillance cameras in underground systems. The sheer extent of such networks poses a challenge to scene interpretation; nevertheless, there is much a priori information and physical constraints (e.g. a train can only move according to a predefined route) to facilitate this task [65] .

The deployment of sensor networks in defense or security applications is primarily for the purpose of providing a common operating picture (COP) and for including redundancy in the system. For the networks to be scalable and be able to provide consistent and succinct information to the users, techniques of distributed and decentralized data fusion [27] [80] [81] have been studied extensively. These systems face a different set of difficulties. These include the problem of ensuring that the information provided by all the sources is trustworthy [105] [114] and the potential for reconfiguration in the event of the loss of one or more sensors [10].

Performance evaluation

A shared concern

How far are we from an operational solution? This question did not have any answer until a series of benchmark data and associated competitions were put forward [91] . Several international and national initiatives have distributed annotated data and organized image understanding competitions. The most famous and still active series of competitions are Pascal VOC [1] for object detection and recognition in internet data, TrecVid [2] video interpretation and PETS [3] for video surveillance problems. These competitions have encouraged research teams to compare their results on the same data and have prompted a global emulation. They have revealed a few things: no tested solution clearly outperforms all of the others on all interpretation problems; performances increase each year, but at a slow rate; some problems are much easier than others. Figure 11 illustrates the evolution of a 20 category detection/localization competition for three different years.

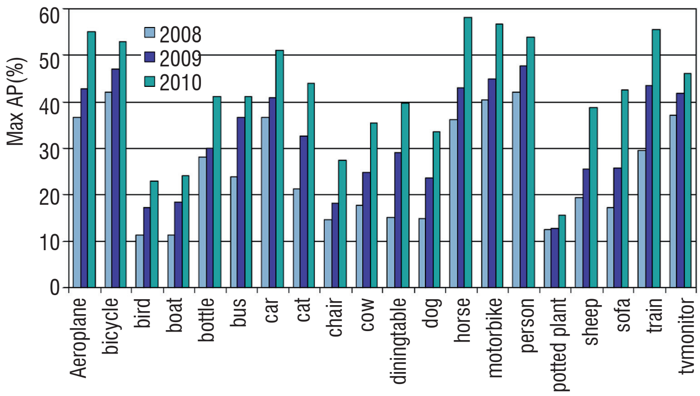


Figure 11 - Progress on the Pascal VOC challenge on three years for the best results on the object localization from 20 categories (http://pascallin.ecs.soton.ac.uk/challenges/VOC/voc2010/workshop/voc_det.pdf)

The aerospace context has no equivalent. The CLIF data set [4] is no longer available outside of the US. The French initiative TechnoVision-ROBIN [33] [34] is no longer maintained. With the growth of interest in aerial and satellite data, it would be beneficial for quantitative evaluation and innovation stimulation to produce and maintain comparable sets of aerospace benchmark data. Possibly the recent dataset for wide area surveillance and containing aerial video [84] will partially address this need.

Processing time

Most of the advanced algorithms for scene understanding are not real-time: the design energy is usually placed on algorithmic innovation, rather than on computing time control. However, with the constant growth of data size, fast algorithms are needed: this is especially true for videos. Several studies are now explicitly addressing the computing time issue, especially with the availability of GP-GPU devices and programming toolkits.

“Fast” image understanding algorithms claim a computing time between a few tenths of a second to a few seconds per image, in general with a parallel implementation. Several bottlenecks are still limiting: low level features used by every stage of scene understanding are, in general, time consuming and should be carefully optimized. Entity detection remains the most demanding step.

Conclusion: What can be expected?

Scene understanding from aerospace sensors follows the general trend of computer vision progress: more robust processing chains, larger domains of exploitation, higher and more refined interpretation levels and better performances both in accuracy and computing time. There has been a noteworthy evolution over the last decade, with the acclimatization of machine learning techniques and a constant development of new image features.

Are the newly developed principles and algorithms really operational? By operational we mean that the processing output can be reliably exploited by non-experts. The answer is not clear-cut. As mentioned in the introduction, simple image understanding algorithms are already used daily, but in situations where their failure is not critical. When embedded into a complex system, a failure may contaminate the entire chain and ruin the confidence in the interpretation.

One should not project too many anthropomorphic expectations on automated scene understanding: algorithms do not think or reason, and have limited experience. However, they are tireless tools, insofar as we can anticipate what they are good at. The next generation of algorithms should therefore integrate reflexive analysis and develop self-diagnosis tools ■

Acronyms

CAD (Computer Aided Design)
C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance)
EO (Electro Optic)
GP-GPU (General Purpose Graphical Processing Unit)
IR (Infrared)
SAR (Synthetic Aperture Radar)
UCAV (Unmanned Combat Aerial Vehicle)
UAV (Unmanned Aerial Vehicle)

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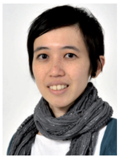

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A Semantic-Based Model to Assess Information for Intelligence

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This paper addresses the problem of information evaluation for Intelligence. Starting from NATO recommendations for assessing information, we propose a semantic-based model to evaluate information. We also define a semi-automatic evaluation process in which an ontology is used, to detect similar items of information. Semantically similar items are then presented to an operator in charge, to estimate their correlations. Items of information are electronic documents exploited for intelligence purposes and they are considered in a broader sense with respect to their form (structured files or free-form text) and their content (description of images of video scenes, HUMINT reports). Linguistic variance, an inherent feature of textual data, can also be handled by using the ontology, while human intervention during the evaluation process ensures a good quality outcome. Finally, we show that this process is compliant with NATO recommendations, while going beyond their limitations.

Introduction

Information evaluation appears as a critical capability for many military applications aimed at offering decision support, since there is an obvious need for valuable information to be transferred at every level of the military chain of command. Information is evaluated by systems able to estimate the degree of confidence that can be assigned to various items of information obtained for intelligence purposes.

In the military field, NATO ([19], [20]) recommendations promote an alphanumeric system for information rating, which takes into account both the *reliability* of the source providing the information and its *credibility*, as it appears when examined in the light of existing knowledge.
Reliability of the source is designated by a letter between A and F expressing various degrees of confidence as follows:

- a source is evaluated A if it is completely reliable. It refers to a tried and trusted source which can be depended upon with confidence
- a source is evaluated B if it is usually reliable. It refers to a source which has been successfully used in the past but for which there is still some element of doubt in particular cases.
- a source is evaluated C if it is fairly reliable. It refers to a source which has occasionally been used in the past and upon which some degree of confidence can be based.
- a source is evaluated D if it is not usually reliable. It refers to a source which has been used in the past but has proved more often than not unreliable.
- a source is evaluated E if it is unreliable. It refers to a source which has been used in the past and has proved unworthy of any confidence.
- a source is evaluated F if its reliability cannot be judged. It refers to a source which has not been used in the past.

Credibility of information is designated by a number between 1 and 6, signifying varying degrees of confidence as defined below:

- If it can be stated with certainty that the reported information originates from another source than the already existing information on the same subject, then it is classified as "confirmed by other sources" and rated 1.
- If the independence of the source of any item of information cannot be guaranteed, but if, from the quantity and quality of previous reports, its likelihood is nevertheless regarded as sufficiently established, then the information should be classified as "probably true" and given a rating of 2.
- If, despite there being insufficient confirmation to establish any higher degree of likelihood, a freshly reported item of information does not conflict with the previously reported behaviour pattern of the target, the item may be classified as "possibly true" and given a rating of 3.
- An item of information which tends to conflict with the previously reported or established behaviour pattern of an intelligence target should be classified as "doubtful" and given a rating of 4
- An item of information which positively contradicts previously reported information or conflicts with the established behaviour pattern of an intelligence target in a marked degree should be classified as "improbable" and given a rating of 5
- An item of information is given a rating of 6 if its truth cannot be judged.

It can be noted that these natural language definitions are imprecise and ambiguous, and they can lead to twofold interpretations. For instance, according to the previous recommendations, the reliability of a source is defined with respect to its previous use, while completely ignoring their current usage context, i.e., the actual environment of use of this source.

As for the credibility of information, the rating defined previously does not qualify a unique property. For instance, how should we note an item of information supported by several sources of information that are also in conflict with some already registered information? According to these definitions, this item should be given a credibility value of 1, but also of 5.

Furthermore, according to NATO recommendations, a rating of 6 should be given to every item whose truth cannot be judged. This supposes that other ratings (1...5) concern the evaluation of information truth value. If so, a rating of 1 corresponds to true information. But, according to its definition, a rating of 1 should be given to an item supported by at least two sources, which is questionable since several different sources may provide false information despite their mutual agreement.

In the light of the discussion above, it becomes obvious that a proper use of those recommendations requires their disambiguation and formalization. The aim of this work is to provide a semantic-based model to evaluate information, based on formal definitions of notions being at the heart of NATO recommendations. It also defines a semi-automatic evaluation process, in which an ontology is used to detect similar items of information. Semantically similar items are then presented to an operator in charge, to estimate their correlations. The underlying applicative scenario of this work implies a timely processing of a constant stream of information provided by various sources, in order to achieve intelligences specific tasks. We consider complex information, such as HUMINT[1] reports or textual descriptions of video scenes. By taking into account semantic aspects it becomes possible to perform enhanced treatments, going beyond key-word spotting and analysis.

The outline of the paper is as follows. First, it presents a brief state of the art on information quality and evaluation, as tackled within various related research fields. "General Framework for information evaluation" introduces formal definitions of the key-notions of NATO recommendations and describes the general architecture supporting the information evaluation process, while "Supporting human opertors through semantics" focuses on the use of ontology to identify semantically similar information items. "Discussion" proves that the outcome of the overall process is consistent with NATO recommendations. Conclusions and future work directions are presented to end this paper.

State of the art

Information evaluation is closely related to the notion of *information quality*. Indeed, traditionally defined as "fitness for use" [14], information quality investigates the estimation of the information capacity to accomplish a specific task, such as information querying, information retrieval or information fusion, for instance. With this respect, information quality appears as a complex notion, covering various aspects. Hence, [3] and [28] identify several dimensions for information quality, among which we found: *intrinsic data quality* (believability, accuracy, objectivity), which is defined by considering the information itself, independently of its production or interpretation frames; *contextual data quality* (relevancy, timeliness, completeness) consists of dimensions related to both *contexts of production* or interpretation of information; *representational data quality* (interpretability, Ease of understanding,) is related to various formalisms used to represent data, having a direct impact on the effective use of that information; finally, *accessibility data quality dimension* concerns protocols to access information, while ensuring their security. In [23], an ontology of information quality attributes is proposed and the issue of combining several of these attributes into a single measure, and of how to take into account quality measure for decision making, is discussed from a semi-automatic fusion system perspective.

Among these various dimensions, *information evaluation* refers to information accuracy, known to be one of the most important dimensions, since it expresses the quality of information being true or correct.

Furthermore, let us mention the relationship between the quality of a model (such an ontology can be) and the quality of information described within this model [27]. According to [27], an information model should be complete (every real world situation can be expressed as an item of information in the model), *unambiguous* (to each item of information expressed in the model corresponds a unique real world situation), *meaningful* (each item of information expressed by the model corresponds to a real world situation) and correct (a user can derive a real world situation from the expressed item of information). Thus, bad quality models lead to bad quality of expressed information; an incomplete model leads to possible unreliable information; an ambiguous model leads to possible imprecise information; a meaningless model leads to possible irrelevant information and an incorrect model leads to possible non-interpretable information.

Since more and more information is produced in heterogeneous and highly dynamic environments, information evaluation emerged as a research topic. Thus, several research efforts have being conducted to estimate the quality of information exploited in various application fields, such as the exploitation of open sources, information retrieval or the management of medical knowledge.

For instance, [3] provides a solution to assess the quality of information retrieved on the Web by defining filtering policies. Those policies combine various meta-data available on data sets, Describing the applicative context of particular information, along with its content, into an overall filtering decision. Policies can be embedded into a browser, allowing the pertinence of its outcome with respect to a user query to be improved, so information is evaluated dynamically. From a different perspective, [15] propose the QUATRO approach for Web content labeling, which ends up with a static qualitative description of Websites. This approach provides a common vocabulary to express quality labels to be assigned to Web content, along with mechanisms to check the validity of those labels. The result of this approach is a unified qualitative description of Websites, which can be taken into account for further treatment, since the information gathered from various sites can be amended by the quality label of its source. Beyond the content itself and its description, Websites also appears as both the source and the target of various links from or to other Websites. [29],[30] consider a link between two pages as an implicit conveyance of trust from the source page to the target page and use these links to define measures expressing trust and distrust of Websites. Moreover, these measures can be propagated through the Web by following the link network. In a more particular context, [24] propose the authority coefficient as a measure characterizing a news blog by

[1] HUMan INTelligence

taking into account its credibility, as assessed by user comments, its confidence, as expressed by the number of pertinent links referred to, and its influence, provided by the number of external sources referring to the news blog considered.

Approaches cited above use external elements, such as various sets of meta-data, user comments, or citations of the considered source by others, while ignoring its own content.

In the medical field, [13] go further and apply information extraction techniques, in order to retrieve valuable information within large amounts of scientific articles and also provide means to characterize this information. Hence, a confidence score is estimated by retrieving linguistic patterns expressing certainty or uncertainty and analyzing the context of information occurrences. While this solution is restricted to a linguistic level, other approaches are performing deeper content analysis, by taking into account the explicit semantics of the application domain. Among them, [10] estimate a coherence coefficient of natural language phrases by mirroring ontological entities appearing in those phrases with respect to an existing ontology. From an interesting perspective, [1] consider both named entities, at a linguistic level, and ontological entities, at a semantic level, to discriminate between negative and positive opinions on news blog threads.

More specifically, many works have addressed the question of information evaluation modeling for military purposes. Most of these can be found in the proceedings of the annual international conference FUSION [8] or in the proceedings of NATO RTO (Research and Technology Organization) symposiums [18]. Let us mention for instance [31], [25] and very recently [26]. All of these works are aimed at defining methods to assess the believability of the information gathered from several sources. These methods take into account different sources with their own degree of reliability, the fact that the item of information considered is consistent or not with previous reported information. Some methods also take into account the fact that, in some cases, the source may include its own assessment of the trustworthiness of the data that it has transmitted.

All of these papers mention NATO STANAG as underlying or motivating their model, but none of them formally prove that their model fulfills the recommendations.

Finally, we would like to mention our own previous works [2][4][5][6][21]. In [2], we have defined information evaluation according to the reliability and competence of the source that provides the item of information and also according to the plausibility and credibility of the item of information. However, a formal relation with NATO recommendations has not been established.

In [4], [5], [6], [21], we have tried to formalize the informal NATO recommendations by proposing formal models. These models are based on the fact that the three main notions underlining the informal NATO recommendations are: the number of independent sources that support an item of information, their reliability and whether the items of information are in conflict or tend to be in conflict. In particular, [4] and [5] present a logical definition of evaluation, based on the number and on the reliability of the sources that supports an item of information. The related fusion method is a weighted sum and is an obvious extension of the majority method defined in [17]with Hamming distance between logical interpretations. [6] proves that this method implicitly takes into account degrees of conflict between items of information.

These works assume that information items are described using logical languages, allowing the implementation of completely automatic reasoning procedures to analyze them. In particular, they assume that the degree of conflict between two items of information is automatically computed. However, these methods prove to be limited when dealing with complex information, such as natural language reports, for instance.

This is why we propose a new solution for information evaluation, going beyond those limitations, since it is able to handle various types of complex information, such as descriptions of video scenes or images, HUMINT reports, etc. This is a semi-automatic approach and it requires human intervention during some key-phases of the evaluation process. Support is provided to the operator when performing the task, since semantically close items of information are gathered together thanks to the ontology. This new approach is detailed hereafter.

A general framework for information evaluation

General architecture

We propose a general architecture for information evaluation, based on basic treatment cells called evaluators, see figure 1.

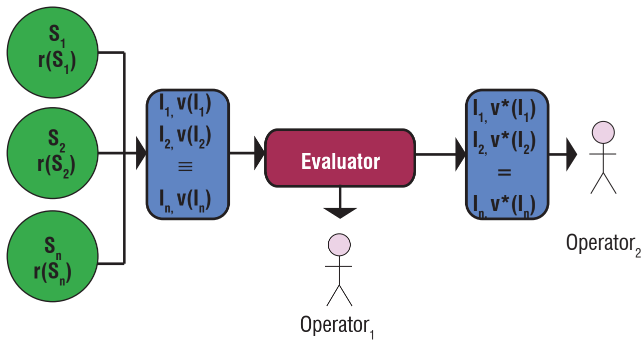

Figure 1 - Architecture for information evaluation

The *evaluator* is a treatment cell managed by an operator, collecting information provided by one or several sources. The input of the evaluator is a set of various information items, while its output is the initial set augmented with confidence scores assigned to each item of information.

Information evaluation is carried out in a semi-automatic manner, with interventions by human operators assessing the quality of each item under analysis. The user can also update the reliability of the sources that provide those items of information.

For this work, the *items of information* to be analyzed are natural language reports, I_1, I_2,.... In emitted by sources named S_1... S_m. Each source S_i is associated with its *degree of reliability* $r(S_i)$, a real number ranging between 0 and 1, where 0 corresponds to a source considered as non-reliable by the operator, while 1 corresponds to a source providing highly reliable information.

Hence, given two sources S_i and S_j:

- $r(S_i) < r(S_j)$ means that the operator thinks that source S_i is less reliable than source S_j.
- $r(S_i) = 0$ means that the operator thinks that S_i is not at all reliable.
- $r(S_i) = 1$ means that the operator thinks that S_i is fully reliable.

In our model, Each item of information is associated with its *evaluation*, denoted by $v(i)$, which is a real number between 0 and 1. Since our starting point are NATO recommendations, the evaluation of information (i) takes into account the two key notions of those recommendations, which are the correlations between various items of information under analysis and the reliability of their sources.

Information correlation

Definition 1 Let I_1 and I_2 be two different items of information. Their degree of correlation, denoted by α_{I_1,I_2}, is a real number in $[-1, +1]$ that the operator will associate with I_1 and I_2 so that:

- $\alpha_{I_1,I_2} < 0$ if and only if I_1 tends to contradict I_2
- $\alpha_{I_1,I_2} > 0$ if and only if I_1 tends to confirm I_2
- $\alpha_{I_1,I_2} = 0$ else.

It's worth noticing that for any two items of information I_1 and I_2, we don't have the property $\alpha_{I_1,I_2} = \alpha_{I_2,I_1}$ since the notion of confirmation is not symmetric.

As a counter-example, consider that I_1 is "It rained last night" and that I_2 is "the road is wet". Given background knowledge according to which rain wets, it is the case that I_1 implies I_2. Thus, $=1$. However, I_2 does not imply I_1. Thus, here <1.

Definition 2 Two items of information I_k and $I_{k'}$ are equivalent in the database of the evaluator $\{I_1 \dots I_n\}$ if and only if:

- $\alpha_{I_k,I_{k'}} = \alpha_{I_{k'},I_k} = 1$
- For any $i = 1 \dots n$ $\alpha_{I_k,I_i} = \alpha_{I_{k'},I_i}$

Information evaluation process

The general process of information evaluation is carried out as follows: each item of information enters the evaluator with its initial evaluation, granted according to the reliability of its source. The more reliable the source is, the more important this value is. This value is then constantly updated by the evaluator, as new items of information are gathered. Thus, at the level of the evaluator, if an item of information is emitted by a source, then its initial evaluation is defined by the reliability degree of the source that emitted it (plus some corrections due, for instance, to the conditions of use of this source; see [2] for the definition of various criteria for the qualification of an item of information).

Assume that the knowledge base of the considered evaluator contains the following items of information: $I_1 \dots I_{n-1}$ associated with their respective current evaluation: $v(1), \dots, v(n-1)$.

Consider a new item of information In, associated with its evaluation *v(n)*. In has been emitted by a source whose reliability is $r(S_n)$. In this case, $v(n) = r(S_n)$, i.e., the current evaluation of In is defined as the degree of reliability of the source that emitted it. Let us denote by the evaluation of any item of information I_k updated after the arrival of I_n.

We define the updated evaluation by:

$$v_k^* = \frac{\sum_{k' \in K_k} (v_{k'} . \alpha_{I_k,I_{k'}}) + |K_k|}{2|K_k|}$$

Where $K_k = \{k' : 1 \le k' \le n,\ k \,^1\, k' \text{ and } \alpha_{I_K, I_{K'}} \,^1\, 0\}$

Notice that: $0 \le v_k^* \le 1$

Indeed, the numerator of the previous fraction is minimal when for any $k' \neq k, \alpha_{I_k,I_{k'}} = -1$ and $v_{K'} = 1$. In this case, it is equal to 0, thus the fraction is equal to 0. Furthermore, the numerator is maximal when for any $k' \neq k, \alpha_{I_k,I_{k'}} = 1$ and $v_{K'} = 1$. In this case, the numerator is equal to $|K_k| + |K_k|$, i.e, $2|K_k$ Due to the denominator, the fraction is equal to 1 in this case.

This function is such that:

- If $I_{k'}$ tends to confirm I_k, then $v_{k'} . \alpha_{I_{k'},I_k} \ge 0$. Indeed $v_{k'} \ge 0$ and $\alpha_{I_{k'},I_k} > 0$. Thus, this factor increases the evaluation of I_k.
- If $I_{k'}$ tends to contradict I_k, then $v_{k'} . \alpha_{I_{k'},I_k} \le 0$. Indeed, Even if $v_{k'} \ge 0, \alpha_{I_{k'},I_k} < 0$. Thus, this factor decreases the evaluation of I_k.
- If $\alpha_{I_{k'},I_k} = 0$, then $v_{k'} . \alpha_{I_{k'},I_k} = 0$. Thus, this factor does not modify the evaluation of I_k.
- If $k=k'$, then $v_{k'} . \alpha_{I_{k'},I_k} \ge 0$ and increases the evaluation of I_k.
- If $v_{K'}^* = 0$ then $v_{k'} . \alpha_{I_{k'},I_k} = 0$ and thus does not modify the evaluation of I_k.

Proposition 1 - If two items of information I_k and $I_{k'}$ are equivalent in the database of the evaluator, then $v_K^* = v_{K'}^*$ whatever v_K and $v_{K'}$ are.

Thus, at the level of the evaluator, human intervention is needed to qualify each item of information under analysis. However, a real time processing of large amounts of information makes manual solution an overwhelming task, especially when information arrives as natural language reports. To cope with this difficulty, we propose a semi-automatic approach, whose treatment regroups various information items according to their semantic similarity, and human intervention is required to analyze them if and only if the semantic similarity is above a given threshold.

Supporting human operators through semantics

In some simple cases, the correlation $\alpha_{I,I'}$ between two items of information I and I' can be computed automatically. More generally, the way correlation degrees can be calculated is related to the way in which information is produced. Assume that the set of valid information that the system manages is finite; then, for every possible pair of items of information, the correlation degree can be pre-defined. For instance, correlation rules can be defined for items of information whose specific elements are date, time and location of events, as we show hereafter.

Example The dating of an event related in a textual document can be done from the extraction of named entities corresponding to the pattern $m/d/y$[2], where m=MM, D=DD, y=YYYY|YY. Now, let us suppose two dates d_1 and d_2 respectively defined by $d_1 = m_1/d_1/y_1$

[2] m stands for month, d for day and y for year.

and $d_2 = m_2 / d_2 / y_2$. For instance, the correlation between d_1 and d_2 can be given by:

- α_{d_1,d_2} iff $d_1 = d_2$
- $\alpha_{d_1,d_2} = 0.9$ iff $d_1 = d_2$ and $m_1 = m_2$ and
  - $y_1 = 20\, y_2$ if y_1 is of the form YYYY and y_2 of the form YY or
  - $20\, y_1 = y_2$ if y_1 is of the form YY and y_2 of the form YYYY
- $\alpha_{d_1,d_2} = -1$ iff $d_1 \neq d_2$ or $m_1 \neq m_2$ or $y_1 \neq y_2$.

However, most of the time, items of information are too complex to have a correlation degree automatically calculated and human intervention is required. In this paper, we propose a semi-automatic approach to estimate the correlation of information items, based on the use of previous knowledge modeled by an ontology. This approach takes advantage of semantic annotations of information items and uses the semantic similarity in order to estimate the correlation between them.

Using ontologies to estimate semantic similarity

According to [9], an ontology is defined as a formal and explicit specification of a shared conceptualization. Ontologies are artifacts modeling domain knowledge by taking into account both the conceptual and linguistic levels. The conceptual level concerns the modeling of field entities, along with the relations that hold between them. The linguistic level is related to the use of natural language terms to name ontological entities. From a linguistic standpoint, named entities are instances of concepts.

By offering this two-fold description of domain knowledge, ontologies offer means to handle the linguistic variety and provide a good basis to perform text analysis by going beyond key-word spotting. On the other hand, the description of items of information by ontological entities allows enhanced reasoning capabilities.

The user is then required to define the degree of correlation between two items of information only if their semantic similarity degree is over a given threshold, as we can see in figure 2.

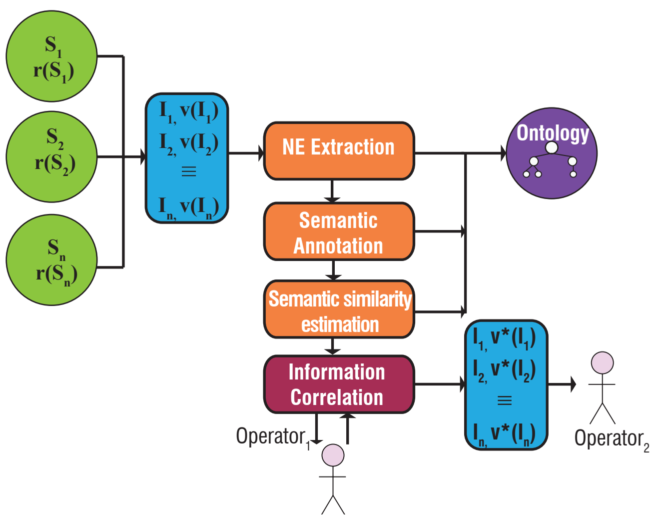

Figure 2 - Semi-automatic evaluation of information

The input of this chain of treatments is the set if information items to be evaluated and it supports treatments for: named entity extraction, semantic annotation and semantic similarity estimation, as described hereafter.

Named entities (NE) extraction

The goal of this processing step is to automatically identify named entities appearing within natural language reports. In order to illustrate our model, let us consider a very simple ontology leading to annotations of the form (where, when, who). This means that named entities retrieved within reports will describe the place of an event (the city, or more precisely, one of its places), time coordinates of the event (date, week day, year) and actors involved (named persons, as well as organizations). We developed a set of pattern matching rules allowing us to automatically identify dates and locations of events.

Example Consider for instance that the information to be collected consists of reports about urban demonstrations. R_1: "*200 étudiants manifestant contre la réforme de la loi sur l'éducation ont affronté les forces de l'ordre sur les Champs Elysées, le mercredi 21 mai, 14h00*" and R_2 : "*Le 21 mai à 15h00, la manifestation des étudiants a pris fin Place de l'Etoile, après une longue marche silencieuse*". Named entity extraction identifies "*Champs Elysées*", and, respectively, "*Place de l'Etoile*". During this phase, "*21 Mai*" will also be identified as the day the manifestation took place.

Semantic annotation

Semantic annotation is about assigning entities or, more generally, information items identified within texts, to their semantic description, as provided by an existing model. Annotation provides additional information about text, so that deeper analysis on its content can be made.

Different techniques and tools of semantic annotation are available. They can be entirely manual: the user himself associates annotations with elements to be annotated, as is the case in [16]. On the other hand, entirely automatic annotation techniques associate annotations with elements to be annotated. By using a set of learned patterns, or an ontology [7],[22]. In between, semi-automatic techniques allow the user to associate annotations with elements to be annotated, by choosing, validating or rejecting annotations proposed by the system [11]. For instance, named entities can be considered as instances of concepts of an existing ontology (ex. Paris is an instance of the concept "city"), therefore it becomes possible to enrich every information item by making explicit relations between named entities previously identified and concepts of an existing ontology.

For this work, a semantic annotation of i is a tuple $(V_i^1,..., V_i^m)$, where each element V_i^k is an instance of some ontological concept. The output of the annotation phase is a set of information $\{I_1 \ldots I_n\}$ with its respective annotation $\{i_1 \ldots i_n\}$, which are instances of a common ontology.

Example In our case, each report will be annotated by a triplet, corresponding to three main concepts of the considered ontology. For instance (*Champs-Elysées*, 05-21-14, Student) annotates the first report, while (*Etoile*, 05-21-14(14h00), Student) annotates the second.

Semantic similarity estimation

Given two annotations $i = (V_i^1,..., V_i^m)$, and $j = (V_j^1,..., V_j^m)$, the degree of semantic similarity between *i* and *j* is defined by:

$$s(i, J) = s_1\left(V_i^1, V_j^1\right) \oplus \ldots \oplus s_m\left(V_i^m, V_j^m\right)$$

where the s_k are some functions of similarity on the classes of the k^{th} values and $\oplus$ is a given aggregation function.

Example Let us take again the (where, when, who) annotations. Here, the three functions s_1, s_2 and s_3 respectively define the similarity between places, dates and people.

Assume that these functions are such that:

- s_1(*Etoile, Champs Elysées*) = .99
- s_2(05-21-14, 05-21-15) = .99 and
- s_3(student, student) = 1

If function $\oplus$ is such .99 $\oplus$ .99 $\oplus$ 1 = .99, then s((*Etoile*, 05-21-14, students),(*Champs Elysées*, 05-21-15, students)) = .99.

This means that according to these different functions, a report relative to a demonstration of students near " *Etoile* " on " May 21st " at "14PM " and a report relative to a demonstration of students near " *Champs Elysées* " on " May 21st " at "15PM " have very high semantic similarity.

A semi-automatic approach to evaluate information

Our objective is that the operator is required to give only the degrees of correlation of items of information I_k, $I_{k'}$ which are ontologically close, i.e., such that $s(I_k, I_{k'})$ is greater than a given threshold γ.
This leads to the following algorithm:

- For any $\boldsymbol{k = 1\ldots n}$ $\alpha_{I_k,I_k} \leftarrow 1$
- For any $k = 1\ldots n$, for any $k' = 1\ldots n$, $k' \neq k \Rightarrow \alpha_{I_k,I_{k'}} \leftarrow 0$
- For any $k = 1\ldots n$, for any $k' = 1\ldots n$, $k' \neq k \Rightarrow$ the semantic similarity $s(I_k, I_{k'})$ is computed.
- If $s(I_k, I_{k'}) > \gamma$ then the information I_k and $I_{k'}$ are transferred to the operator in order he estimates their degrees of correlation $\alpha_{I_k,I_{k'}}$ and $\alpha_{I_{k'},I_k}$

Two items of information relative to the same place, the same date and the same persons are ontologically close, but they may contradict or confirm each other, while two items of information that are ontologically distant will maintain a null degree of correlation.

Notice that the evaluation of the degrees of correlation by the human operator is necessary, since two items of information that are semantically close do not necessarily confirm each other. For instance, a report stating " the demonstration has been followed by a huge number of students near *Etoile* on May 21st at 14PM " and the information "only few students in the streets nearby *Champs Elysées* on May 21st at 14PM " are ontologically close, but they are contradictory. However, the use of a finer ontology, allowing richer semantic annotations, makes it possible to emphasize the contradiction between those items of information (due to the presence of " few students " and " a huge number of students ", which are contradictory quantifiers).

Discussion

The question that we address here is now: does the information evaluation model described in this paper agree with the informal requirements of NATO?

We aim to prove that this model agrees with these, by showing that it takes into account the three main notions that underline these requirements, which are the number of independent sources that support the information, their reliability and the fact that items of information are contradictory or tend to be contradictory.

• The previous model obviously takes into account the number of independent sources that support an item of information and their reliability. More precisely, the more supported an item of information is and the more reliable its sources are, then the higher its evaluation is. Indeed, for a given k, let us denote:

$S_k^1 = \{k'=1\ldots n,\ \alpha_{I_k,I_{k'}} > 0\}$ and $S_k^2 = \{k'=1\ldots n,\ \alpha_{I_k,I_{k'}} < 0\}$

Thus, we can write:

$$v_k^* = A + B\left(\sum_{k'\in S_k^1} v_{k'}\alpha_{I_k,I_{k'}}\right) + B\left(\sum_{k'\in S_k^2} v_{k'}\alpha_{I_k,I_{k'}}\right)$$

where A and B are constants, that permit the following properties to be exhibited.

Proposition 2

1. If the number of sources that support information I_k increases, then $\sum_{k'\in S_k^1} v_{k'}$ increases. Thus, v_k^* increases.

2. If the degrees of reliability of the sources that support Ik increase, then $\sum_{k'\in S_k^1} v_{k'}$ increases. Thus, v_k^* increases.

• The information evaluation model previously defined takes into account the fact that items of information are contradictory, or tend to contradict each other.

Indeed, we can obviously define a notion of degree of conflict from the notion of degree of correlation. Let I_1 and I_2 be two different items of information. Their degree of conflict, noted by $c(I_1, I_2)$, can be defined by: $c(I_1, I_2) = -\alpha_{I_1,I_2}$. Notice that $c(I_1, I_2) \in [-1, +1]$.

Proposition3

- $c(I, I) = -1$
- $c(I_1, I_2) > 0$ iff I_1 tends to contradict I_2.
- $c(I_1, I_2) < 0$ iff I_1 tends to confirm I_2.
- $c(I_1, I_2) = 0$ else.

Conclusions and future work

In this paper we tackled the problem of information evaluation for intelligences purposes, from a military specific point of view. We considered the evaluation of complex information, such as natural language reports. We defined the general architecture of an evaluation system, based on a basic treatment cell called an evaluator. We also addressed semantic aspects and showed how an ontology can be used to annotate information items and to define a semantic similarity degree between them. We claimed that the operator of an evaluator must be required to examine items of information only when their degree of similarity is over a given threshold. In this case, the operator has to assess their degree of correlation. In the model that we defined, the overall evaluation of information has two ingredients: the correlation degree of a particular information item with respect to other information items under analysis and the reliability of its source.

Finally, we showed that this model is compliant with respect to informal requirements for information evaluation, as expressed by NATO, in the sense that it takes into account the main notions underlying those recommendations.

It must be emphasized that the evaluation values computed according to the process that we defined depends strongly on the ontology that is considered and on the different constants and functions mentioned in § "Semi Automatic Approach" such as: the similarity functions, the aggregation function and the value of the threshold. Indeed, the ontology and these functions and constants are used to relate semantically similar reports or, equivalently, to discriminate non-similar reports.

Of course, the evaluation values computed according to this process also depend on the user, who is required to estimate the correlation degrees between similar reports.

Notice that the fact that our process is semi-automatic implies that the classic evaluation methods (benchmarking with recall and precision measures) are not suitable to validate it. To measure the real advantages offered by our system, we must measure the time that is necessary for an operator to calculate the correlation degrees of items of information, with and without the help of the system, and compare them.

The implementation of this general process is under development and will lead to an experimental validation of the ideas. However, as mentioned previously, one question concerns the choice of the different constants and functions used in the process. Currently, it is difficult to estimate how the overall information evaluation varies according to the choices of these functions and thresholds. One future work direction is to study the impact of such choices on the resulting evaluation.

Another direction concerns the improvement of semantic similarity estimation, by also taking into account ontology concepts, since for now only their instances are considered. For this purpose, enhanced information extraction treatments are needed, to retrieve concepts within texts. Once identified, these concepts can be a part of the semantic annotation and they can be used to define more accurate measures for semantic similarity.

Since natural language reports are complex data, the main limitation of our approach is related to textual data processing. Therefore, linguistic phenomena such as negations are not taken into account during the automatic processing of our data. Instead, user intervention can easily identify them and asses or reject the correlation of information items. From an applicative point of view, the notion of contradictory information items is not addressed by automatic procedures, since the role of the user is to identify such contradictions within a collection of correlated information items. Hence, adopting this user-centric approach to evaluate information allows us to accomplish a satisfactory level, in terms of information quality ■

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Authority Management and Conflict Solving in Human-Machine Systems

This paper focuses on vehicle-embedded decision autonomy and the human operator's role in so-called autonomous systems. Autonomy control and authority sharing are discussed, and the possible effects of authority conflicts on the human operator's cognition and situation awareness are highlighted. As an illustration, an experiment conducted at ISAE (the French Aeronautical and Space Institute) shows that the occurrence of a conflict leads to a perseveration behavior and attentional tunneling of the operator. Formal methods are discussed to infer such attentional impairment from the monitoring of physiological and behavioral measures and some results are given.

Introduction

There is a growing interest in unmanned vehicles for civilian or military applications, since they prevent the exposure of human operators to hazardous situations. In these domains, autonomy is crucial because the human operator is not embedded within the system [50] and hazardous events may interfere with the human-robot interactions (e.g. communication breakdowns and latencies). The design of authority sharing is therefore critical [29], because conflicts between the robot and the human operator are likely to compromise the mission [38, 52]. Interestingly, these findings are consistent with research in aviation psychology: crew-automation conflicts known as "automation surprises" [40, 41] occur when the autopilot does not behave as expected by the crew (e.g. the autopilot has disconnected and the crew, who is not flying, is not aware of that [35]). These situations can lead to accidents with an airworthy airplane if, despite the presence of auditory warnings [3], the crew persists in solving a minor conflict [4] «instead of switching to another means or a more direct means to accomplish their flight path management goals» [56]. Flight simulator experiments show that in the case of a cognitive conflict with the mission management systems, the human operators' attentional resources are almost exclusively engaged in solving the conflict [17] to the extent that critical information such as visual or auditory alarms are neglected [18] - a phenomenon known as attentional tunneling [54].

Conflicts in a human-machine system stem from the fact that either the plan for the human operator or the machine is not being followed anymore, or the operator has a faulty awareness of the situation [53], or both. In order to prevent mission degradation, the agents' plans and, if need be, the authority allocation must be adapted, either to fit in with the authority change, or to go against it. This is a real challenge, since in human-machine systems the human agent is hardly controllable and no "model" of the human's decision processes is available. In this paper we will focus on autonomy and the human operator's role in autonomous systems. Then autonomy control will be discussed, before highlighting authority sharing and authority conflicts and discussing the possible effects of such authority conflicts on the human operator's cognition and situation awareness. As an illustration, we will highlight an experiment conducted at ISAE (the French Aeronautical and Space Institute) to show that the occurrence of a conflict leads to a perseveration behavior and attentional tunneling and that such an attentional impairment can be inferred thanks to the monitoring of physiological and behavioral measures.

Box 1 - Perseveration and attentional tunneling

Lessons learned from aeronautics and recent experimental research in aeronautics [17, 37] have shown that the occurrence of a conflict during flight management (e.g.: pilot-system conflict, pilot-co-pilot conflict, etc.) causes cognitive and emotional disorders and leads to perseveration. This particular behavior, which is studied in neuropsychology [51] and psychology [2], is known to summon up all of the pilot's mental efforts toward a single objective (excessive focus on a single display or focus of the pilot's reasoning on a single task). Once entangled in perseveration, the pilot does anything to succeed in their objective even if it is dangerous in terms of safety. His attentional abilities are impaired, with a tendency to attentional tunneling: any kind of information that could question his reasoning (like alarms or data on displays) is ignored. These findings are akin to a recently published report of the BEA (the French national institute for air accident analysis) that reveals that attentional tunneling has been responsible for more than 40% of casualties in air crashes (light aircraft).

Autonomy and the human operator's role

In this paper, autonomy stands for decision autonomy, i.e. an "autonomous" agent has the ability to make decisions on its own with embedded situation assessment and decision and planning functions. In ALFUS, methodology autonomy is defined as "a UMS's own ability of sensing, perceiving, analyzing, communicating, planning, decision-making, and acting/executing, to achieve its goals as assigned by its human operator(s) through designed HRI [30]".

While there is no universal definition of autonomy, this concept can be seen as a relational notion between some agents about an object [9, 6]: agent X is autonomous with respect to agent Y about goal G. In a social context, other agents or institutions may influence a given agent, thus affecting its decision making freedom and its behavior [8]. In the context of a robot or software agent in the real world, autonomy can be seen as the ability of the agent to minimize the need of human supervision and to act alone [43]: the primary focus is then the operational aspect of autonomy rather than the social one. In this context, pure autonomy is just a particular case of the artificial agent - human agent relationship, precisely consisting in not using this relationship. However, in practice, human supervision is needed since (1) algorithms can only do what they are designed for and cannot cope with unknown situations [7]; (2) some decisions must be taken by a human being (e.g. in military contexts); (3) the human operator must be able to take over from the algorithms. Moreover, it seems that human interventions significantly improve performance over time compared to a neglected agent [24, 23]: neglect corresponds to communication delays between the human operator and the artificial agent or moments when the human operator is absent or busy with other tasks. Therefore autonomy is still needed to make up for neglect, especially when the operators are far away and communication is not permanent (for security reasons or because of the physics of the system, e.g. the space domain).

In order to take advantage of the complementary skills of the human and artificial agents [31], autonomy variation has been widely considered in the literature:

- Evaluative approaches such as MAP (Mobility, Acquisition and Protection) [26, 11], ACL (Autonomous Control Level) [11] or ALFUS [28] a posteriori assess the autonomy of a robot agent used in a particular mission. Nevertheless, the assessments are either very general and qualitative (ACL), or quantitative with a lack of semantics (e.g. ALFUS final score is an aggregation of three different scores assessing mission complexity, environmental complexity and human independence [30]).
- Prescriptive approaches focus on the design of "autonomous" systems, including human control, with the issues of autonomy levels and how to switch levels. These approaches a several features, i.e. the roles and tasks of each agent within the system, initiative modes, the criteria for autonomy evolution and how the human operator is perceived by the artificial agent. They are dealt with in the next section.

Box 2 - Automation vs. Autonomy

Both terms refer to processes that may be executed independently from start to finish without human intervention. Automated processes simply replace routine manual processes with software/hardware ones that follow a step-by-step sequence, which may include human participation. Autonomous processes, on the other hand, have the more ambitious goal of emulating human processes rather than simply replacing them [49]. It is the difference between a washing machine and a scouting mission: the first one performs human-less operation whereas the second one shows human-like performance [30].
Example: a cruise missile is not autonomous but automatic since all choices have been made prior to launch [11].

Autonomy variation and autonomy control

Roles and tasks

A role is designed as a set of tasks to be achieved by a given agent [25]. Autonomy-level based prescriptive approaches then specify how the roles should be shared out between the human and the artificial agent. As early as in 1978 Sheridan [47] published a ten-level automation scale for a robotic system: nevertheless, it is an abstract model that does not take into account the environment complexity, or the mission of the robot. Since then, several other scales have been proposed, e.g. [19] for which an autonomy level is characterized by the complexity of the processed controls, [24] where a level represents the capacity of the robot to work independently from the human operator or [5] which claim that the agents' roles vary according to the tasks they must do, they are allowed to do or can do, and the initiative they have to perform them.

The main limits of these approaches are the following:

- at a given autonomy level, the agents' roles cannot evolve;

• there is a limited number of levels, therefore a rigid framework is set and the variety of the situations encountered during a mission cannot be taken into account;

• no rules are given to switch levels;

• the scales are either very general and abstract, or dedicated to a particular system.

Autonomy may also be considered at the task level [46, 21]: an agent is autonomous to achieve a task whenever this task is allocated to it. This approach is more appropriate to deal with the features of a particular mission, nevertheless defining the “best” agent to achieve a given task is an issue in itself.

Initiative modes

Initiative modes are related to the dynamics of the artificial agents’ autonomy: which of the artificial agent and the human agent can change the autonomy level of the artificial agent? Three initiative modes are highlighted in the literature: adaptive autonomy, giving the artificial agent exclusive control; adjustable autonomy, giving the human agent exclusive control; and mixed initiative, where the human and artificial agents collaborate to maintain the best perceived level of autonomy [25].

Adaptive autonomy mainly implements the capacity of the artificial agent to ask for the human operator’s help, or to self-control. For instance [42] endow robot agents with learning capabilities allowing them to better manage the need for human intervention. Fong’s collaborative control [22] is an approach aimed at creating dialogs between the operator and the robot: the robot sends requests to the human operator when problems occur so that these are able to provide the needed support. [10] design agents that can diagnose their own states and self-adapt thanks to predefined behaviors.

The main advantage of adaptive autonomy is that it allows the behaviors of the artificial agent to be well defined for well-identified tasks and situations. Moreover, reactions may be triggered faster than under human control. However, human operators cannot take over from the artificial agent whenever they want, especially when they believe the artificial agent behaves wrongly: their interaction with the artificial agent is restricted to what is expected from them [25].

On the contrary, adjustable autonomy is when only the human operator can control the artificial agent autonomy: the operator may choose the interaction level [19] or “advise” the artificial agent through behavioral or enabling rules [36]. Then, the human operator can analyze the situation, anticipate disruptive events and take over from the artificial agent. The main drawback is that performance may decrease when the operator reacts too slowly or wrongly: the human operator’s actions on the artificial agent are not always beneficial [45].

The underlying idea of mixed initiative is to take advantage of the skills of both agents. [46] base task allocation between the robot and the operator on statistics to determine which agent will be the most efficient. This does not guarantee success, because statistics summarize very different situations. However, autonomy tuning at the task level is an interesting idea, since it provides the most adaptive solution to the mission. On a similar principle, [44] build a model allowing artificial agents and human operators to transfer decision making to each other and to compare their decisions. Inconsistencies in the team can be detected so that they can be solved. While the idea of inconsistencies seems to be really relevant in the context of a team of agents, the authors do not say how they should be solved: who should have the priority if the artificial agent and the human operator disagree?

Mixed initiative seems to be the best approach, however it must be tuned properly to show its benefits in practice [25].

Criteria for autonomy evolution

As far as adaptive autonomy and mixed initiative are concerned several operational criteria have been proposed for the artificial agent to change its autonomy. Markov Decision Processes are proposed by [42] and [44], in order for the artificial agent to decide changes, especially to give the authority to the human agent. Furthermore, [44] deal with the possible inconsistencies among the agents’ decisions. Such an approach needs to be able to compute the utility of each strategy. The criteria of [25] are explicit, since autonomy changes are triggered by predefined events (i.e. some human operator’s actions, some mission events). Those criteria are objective, however they are very mission- and task-dependent. As far as the work of [36] is concerned, the behavior of the robot agent changes according to predefined rules; however, the potential conflicts between rules are not discussed.

Various criteria and metrics have been proposed in the literature to trigger autonomy changes in the artificial agent. Though they are grounded on objective mission features, they are generally very mission-dependent and therefore not re-usable in other contexts.

How is the human operator perceived by the artificial agent?

Generally speaking and even if it is likely to be erroneous, the human operator has knowledge of the capacities of the artificial agent and of its current and possible future states (situation awareness [20]). Conversely, when adaptive autonomy or mixed initiative are considered, the artificial agent should have a model of the human operator’s “capacities” and “state”. This is hardly the case in the literature, since the operator is often considered as an infallible resort. Some examples however can be found [31, 21] where the robot has models of the tasks the operator can perform: therefore, it can plan for itself and for the operator and track the operator’s task execution.

More recent research [1, 12] considers some data from the operator (such as physiological data, eye tracking, expertise, workload) to take part in the reasoning process of the artificial agent, thus allowing it to adapt its autonomy when an “impaired state” of the operator is diagnosed. We will focus on that approach in the rest of the paper.

From autonomy to authority

Joining human and machine abilities aims at increasing the range of actions of “autonomous” systems. However, the relationship between both agents is dissymmetric, since the human operator’s “failures” are often neglected when designing the system. Moreover, simultaneous decisions and actions of the artificial and the human agents are likely to create conflicts [16]: unexpected or misunderstood authority changes may lead to inefficient, dangerous or catastrophic situations. Therefore, in order to consider the human agent and the artificial agent in the same way [27] and the human-machine system as a whole [55], it seems more relevant to work on authority and authority control than on autonomy, which concerns the artificial agent exclusively.

Authority sharing and authority conflicts

One of the main issues in human-machine systems is to prevent the whole system from deteriorating and reaching undesired and possible dangerous states; this includes on-line failure detection and recovery, the maintenance of the operator's situation awareness and correct interaction with the artificial agent, as well as authority conflict detection and solving.

A change in authority allocation can be planned in the procedures or in the mission plan, or can be unexpected: this happens when the human operator takes over a task controlled by the artificial agent (software or robot) because they detect a failure, or for any reason of their own; or when the artificial agent takes over a task controlled by the operator because the operator's action violates some constraints (e.g. a potential excursion out of the flight domain), or because the communication with the operator is impaired; or when no agent has the authority anymore [35]. Therefore authority has to be formalized in order to identify those situations so as potential authority conflicts.

Authority: some definitions

An agent X has authority over a resource R of a system with respect to another agent Y [34] if X can control R to the detriment of Y. The control of X on R can be more or less strong against Y according to the following modes:

- access: agent X can use resource R in order to achieve a goal;
- pre-emptability: agent X can use resource R as soon as needed, taking it from agent Y if Y is already controlling R;
- control guarantee: once agent X controls R, agent Y will not be able to take R away from X through pre-emption.

Consequently authority is characterized by the following properties:

- a gradation of the agent's authority: agent X's control on resource R gets stronger as it is granted access, pre-emptability and control guarantee, in this order;
- authority, as autonomy [9] is a relative concept: agent X may have pre-emptability on R over agent Y, but not over agent Z. Consequently, there are as many authority relationships as there are couples of agents that may control R;
- authority is shared between the agents: for a couple of agents <X,Y> that may control resource R, the authority gain of agent X on resource R corresponds to an authority loss for agent Y. For instance, if agent X obtains the control guarantee on R, this means agent Y loses pre-emptability. Consequently, agent Y will not have access to R anymore: agent X prevents agent Y from accessing resource R, even if it does not use it.

The Petri net in figure 1 represents the authority relationship between two agents, X et Y, for a given resource R: each place corresponds to the State of agent X / State of agent Y regarding resource R. The state changes modify the status of R, i.e. they determine whether R can be allocated to X or Y, or not.

There are two intermediate states for which the agents' authority is equivalent, namely (Access / Access) and (Pre-emptability / Pre-emptability). As far as the first one is concerned, the agents cannot take the resource control from one another, each must wait for the other one to release the resource. This is a cooperation context. As far as the second one is concerned, the agents can take the resource control from one another indefinitely, which makes the behavior of the system inefficient or even dangerous. This is a competition context.

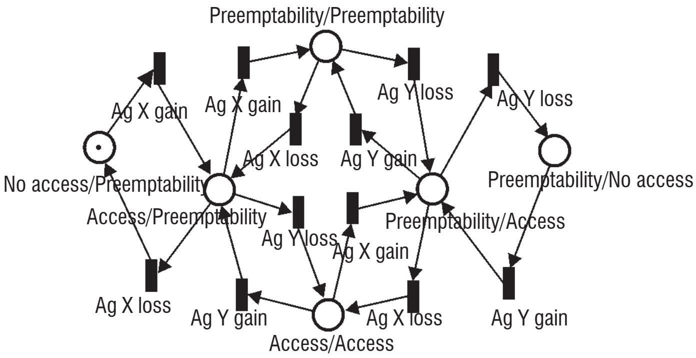

Figure 1 - Authority relationship between two agents X and Y on a given resource R

Authority conflicts

A conflict is a state of the world where one or several agents cannot achieve their goals: agent X is in conflict with agent Y if one of Y's goals prevents X from achieving one of its goals. Except for state (Access / Access), which corresponds to both agents having the lowest authority over resource R, all other states of the authority relationship are potential conflicts, since one agent has more authority than the other over R, or both agents have Pre-emptability (competition for R). Authority conflicts between the human operator and "autonomous" systems are often linked to "automation surprise" [41]: either the plan for both the human and robot is not followed anymore, or the operator has a faulty awareness of the situation [53], or both.

Experiments conducted in flight simulators reveal that the occurrence of such conflicts in mission management systems [17] leads to summoning up most of the human operator's capacities toward conflict solving. As a consequence, the operator's cognitive abilities are impaired with a strong tendency to attentional tunneling [54], where critical information, such as visual or audio alarms [18], is neglected. Because this critical information is not perceived, the human operator's situation awareness is degraded, which may lead to a dangerous vicious circle (see figure 2).

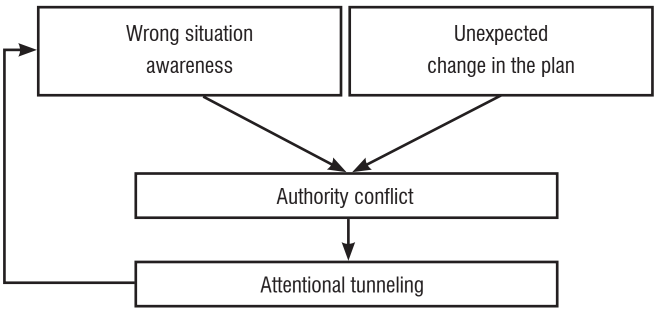

Figure 2 - The vicious circle of authority conflicts

Conflict detection and solving

Conflict detection and solving in human-machine systems involve (figure 3):

- an estimation of the state of the whole human-robot system, i.e. an estimation of the state of the robot, of the «state» of the human operator and of the state of the interaction between the two; conflicts

Box 3 - Cognitive countermeasures

Attentional tunneling is a paradox for interface designers: how can one expect to "cure" human operators from attentional tunneling if the alarms or systems designed to warn them are neglected? Experiments conducted in flight simulators have shown that the absence of response to either auditory or visual alarms may be explained by an inability to disengage attention: the warning systems are based on providing the operator with additional information, but this is of little use if the warning system is not also efficient in disengaging attention from the current task [17]. By contrast, cognitive countermeasures are based on the temporary removal of information on which the human operator is focusing, for it to be replaced by an explicit visual stimulus in order to change the operator's attentional focus. The user interface acts as a cognitive prosthesis as it performs the attentional disengagement and attentional shifting.

correspond to inconsistent or unwanted states of the human-robot system;

• conflict solving thanks to an adaptation of the human-machine system, i.e. re-planning, changes in authority sharing [34, 33], cognitive countermeasure sending [18].

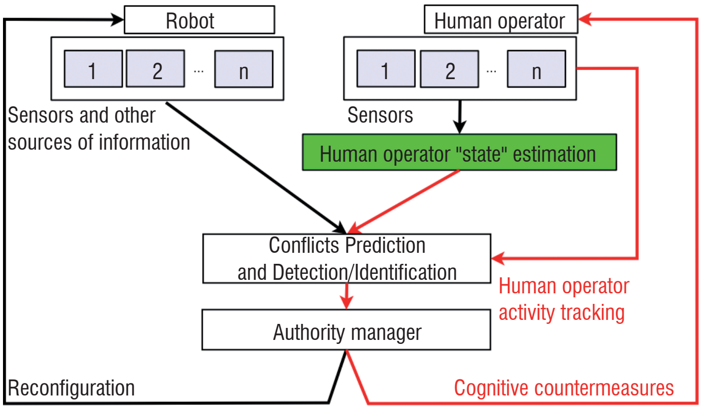

Figure 3 - Conflict solving and the role of the human operator "state" estimation

State estimation

State estimation results from the matching between measures and models of the expected behaviors of the human-machine system. Conflict markers are inconsistent states (e.g. a dead marking in a Petri net representing the operation of the system), and/or measures matching a model of an unwanted behavior (e.g. the operator's attentional tunneling).

Several kinds of measures are required to estimate the state of the human-machine system: some measures linked to the state of the physical system (the machine), e.g. the configuration, the speed, the alarms, etc.; some measures linked to the "state" of the human operator; and some measures linked to the interaction between the human and the machine, e.g. the operator's actions on the machine interfaces. The analysis of these different state vector estimations allows the current and future situations to be assessed in order to adapt the tasks and the authority of both the human and artificial agents.

The estimation of the «state» of the human operator is a challenge. Indeed both data and models for recognizing special «states» are needed. As far as attentional tunneling is concerned, the human operator's excessive focus is associated with a decreased saccadic activity and long concentrated eye fixations [13] and consequently less scanned areas of interest on the user interface [48]. The heart rate also confirms that the catabolic activity increases. Therefore models of those phenomena have to be built or learnt [32] to further characterize unwanted "states" of the operator.

Conflict solving

Conflict solving consists in adapting the behavior of the machine and the information sent to the human operator, at least for a while. This may involve:

• action re-planning and/or resource reallocation within the system (e.g. in case of a failure), possibly with goal changes (e.g. land on the nearest emergency landing ground);

• changes in some authority relationships on some resources of the human-machine system [33] (e.g. automatic protection of the flight domain: the autopilot can take over from the crew);

• cognitive countermeasure sending to the human operator, through the HMI [17, 18, 14] (e.g. in case of attentional tunneling in the human operator).

An experiment and some results

This section is focused on an experiment and first results that we have obtained for conflict identification and solving. More details can be found in [39, 14 and 15].

Experimental framework

Experiments have been conducted at ISAE on a target search mission achieved by a ground robot and a remote human operator [33, 15]. The human operator is equipped with an eye-tracker and with an electrocardiogram device. The robot is equipped with decision functions that allow it to navigate while avoiding obstacles, to detect targets and to adapt its behavior when some disruptive events occur. Information is available on the HMI (see Figure 4) for the human operator to supervise the robot and take over if necessary. As soon as a target is detected by the robot, the operator must take over and operate the robot so as to identify the target precisely.

While the operator takes over the robot for target identification, a battery failure triggered by the experimenter activates a safety procedure that makes the robot go back to base autonomously. This event is presented on the operator's interface via three alarms: the battery icon (Area 7) switches from green to orange, the piloting mode (Area 3) blinks twice from «manual» to «supervised», and the display (Area 5) shows «Back to base» in green. However, since this unexpected event occurs at a critical time in the mission when the operator is particularly focused on the panoramic vision

Figure 4 - The human-machine interface

Video 1: despite the alarms, the operator's gaze (red cross) is fixed on the panoramic vision display. http://www.aerospacelab-journal.org/al4/authority-management-and-conflict-solving

Video 2: the countermeasure disengages the operator's visual focus (red cross) from the panoramic vision and leads him to glance at the battery icon within 1 second. http://www.aerospacelab-journal.org/al4/authority-management-and-conflict-solving

display (Area 8) for the identification task in manual mode, the results show that 9 participants out of 13 faced attentional tunneling and were not aware of the automation logic: the eye-tracking data showed that the relevant information (Areas 3, 5 and 7) had not been seen (see video 1). Consequently, each agent (the robot and the operator) persisted in fulfilling their goals, i.e. going back to base and identifying targets respectively. This is an authority conflict concerning the control of resource "robot navigation" with a (Pre-emptability / Pre-emptability) competitive state of both agents (figure 1).

Conflict solving through countermeasures

A second experiment was conducted with 11 subjects. The goal was to test empirically one of the possible actions to solve a conflict, i.e. a planned interaction with the operator aimed at modifying the operator's behavior: this cognitive countermeasure consists in removing the panoramic vision display (Area 8) where the operator is focused, and replacing it during 4 seconds with the message "Battery failure, robot returning to base" (see video 2). What is expected is that the operator will drop their target identification task and switch their attention towards the relevant areas of the interface.

The results show that 9 participants out of 11 immediately gave the control back to the robot to let it return to base autonomously. The remaining two participants claimed that they had understood the conflict with the countermeasure, but thought that they had enough time to operate the robot before the total discharge of the battery.

Characterization of attentional tunneling

Characterizing attentional tunneling is necessary to design models (figure 5 left) so as to be able to automatically detect this phenomenon on-line (figure 5 right) and trigger relevant actions to compensate for it.

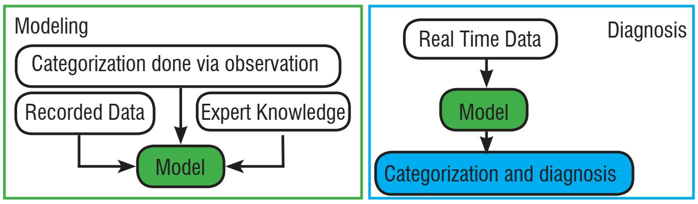

Figure 5: The model is designed (left) to be used on-line (right)

Thanks to signal processing of the data collected during the experiments (i.e. the operator's gaze position and heart rate) and fuzzy aggregation rules, first characterizations of attention tunneling have been obtained. The measures - percentage of time spent on the video (Area 8), number of areas of interest (AOIs) scanned in a defined time interval, number of changes of AOIs in a defined time interval; heart rate and heart rate standard deviation - are aggregated thanks to expert rules so as to derive the Focus and the Cardiac Stress which are in turn aggregated to derive the Attentional Tunneling - see [39] for more details.

As an example, figures 6 and 7 show the results for two subjects previously labeled by the experimenters as “Attentional tunneling” and “OK, conflict perceived” respectively.

Time references on the x-axis (graduated in seconds) are: P1: start of phase “research area”; P2: start of phase “search target”; P3: start of phase “identify target” (i.e. manual piloting); P4: failing battery alarms, piloting mode «supervised”, start of the conflict; P5 (if present): observed end of the conflict. On the time axis the alert level is represented by a three-color code (red, yellow and green).

As we can see for case A, the alert level goes from low (green) to high (red) during manual piloting. The alert level is stable on high for the rest of the mission. This is in accordance with the observed behavior: the subject faced attentional tunneling and did not understand the conflict.

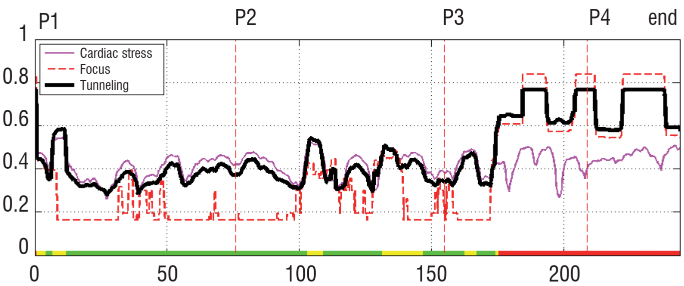

Figure 6: Case A - Attentional tunneling

As for case B, the alert level goes from low to high during manual piloting. After the start of the conflict the alert level is stable on high. After the end of the conflict the alert level goes from high to medium (yellow) in about 5 seconds and from medium to low in about 5 more seconds. In this case also the calculated behavior is in accordance with the observed behavior.

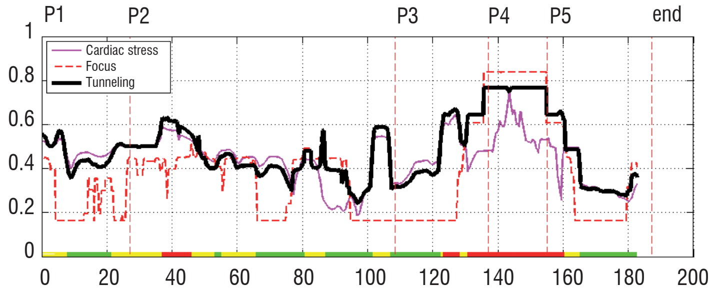

Figure 7: Case B - OK, conflict perceived

Conclusions and further work

The main drawback of the concept of variable autonomy – though widely studied in the literature – is that the human operator is not placed on the same plane as the machine (a robot or a software agent): the human operator is often considered as an infallible resort within the human-machine system. On the other hand, the concept of authority allows symmetric roles to be considered: the authority on a given resource can be transferred from one agent to the other according to the context. Furthermore, the concept of conflict allows degraded situations within the whole human-machine system to be detected, provided measures that are relevant to identify or predict unwanted behaviors are available. Therefore, some models of the operator's specific behaviors must be designed. We have shown that model building from experimental data gives promising results as far as attentional tunneling is concerned.

The main challenge in human-machine mixed initiative systems, such as robots or aircraft, is to avoid conflicting situations, i.e. situations where the operator and the decision algorithms “do not understand each other” and attempt to keep their authority on some resources of the system. Further work must focus on the closed loop involving on-line conflict detection – thanks to further investigation of the “human” metrics and of the correlation of the “human” and “machine” metrics, and the design of robust models of degraded human behaviors; and on on-line conflict solving through authority dynamic management, so as to allocate authority to the most capable agent in the current context. This involves further issues, such as agents' cohesion, the maintenance of the human operator's situation awareness and the operator's acceptance. Solutions allowing the operator's actions to be influenced without disturbing them (e.g. “subliminal” guidance, actions on the operator's situation awareness using countermeasures, etc.) must be further investigated ■

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Acronyms:

ALFUS (Autonomy Levels For Unmanned Systems Framework)
AOI (Area Of Interest)
BEA (the French national institute for air accident analysis)
ISAE (the French Aeronautical and Space Institute)
UAV (Unmanned Aerial Vehicle)
UGV (Unmanned Ground Vehicle)
UMS (UnManned System)
HMI (Human Machine Interface)
HRI (Human Robot Interaction)

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Sense of Control in Supervision Tasks of Automated Systems

We live in an increasingly technological world. Automated systems certainly can make life easier, but they can also create complexity and uncertainty. Moreover, it is clear that automation does not merely supplant human activity, but also transforms the nature of human work. This review examines an original account of this transformation – a link between automation technology and the sense that our actions cause effects on the outside world (so-called 'agency'). Accordingly, we first discuss the human factor issues related to automation technology. Particularly, we introduce the out-of-the-loop performance problem. Then, we introduce recent findings about agency. We propose that several recently developed psychological approaches to the self-promise to enhance our comprehension of the transformation induced by increased automation. Next, we address the controversial issue of agency measuring, particularly the necessary dissociation between explicit and implicit agency measurement. In particular, we introduce the intentional binding effect as an implicit agency measurement, and we discuss the problems and issues related to the generalization of this effect to more complex situations. Finally, we suggest that the investigation of this authorship processing in the field of human-machine interaction may be fruitful, both to elaborate concrete design recommendations and to evaluate the potentiality for an HMI to satisfy the agency mechanism.

Automation and human control in complex systems

"The burning question of the near future will not be how much work a man can do safely, but how little." [85]

There is perhaps no facet of modern society in which the influence of automation technology has not been felt. Whether at work or at home, while travelling or while engaged in leisurely pursuits, human beings are becoming increasingly accustomed to using and interacting with sophisticated computer systems designed to assist them in their activities. Even more radical changes are anticipated in the future, as computers increase in power, speed and "intelligence".

We have usually focused on the perceived benefits of new automated or computerized devices. This is perhaps not surprising, given the sophistication and ingenuity of design of many such systems (e.g., the automatic landing of a jumbo jet, or the docking of two spacecraft). The economic benefits that automation can provide, or is perceived to offer, also tend to focus public attention on the technical capabilities of automation. However, our fascination with the possibilities afforded by technology often obscures the fact that new computerized and automated devices also create new burdens and complexities for the individuals and teams of practitioners responsible for operating, troubleshooting and managing high-consequence systems. Whatever the merits of any particular automation technology, it is clear that automation does not merely supplant human activity but also transforms the nature of human work. As a matter of fact, the role of the human actors may possibly evolve from direct control to supervision. Understanding the characteristics of this transformation is vital for successful design of new automated systems.

Automation and OOL performance problem

When new automation is introduced into a system, or when there is an increase in the autonomy of automated systems, developers often assume that adding "automation" is a simple substitution of a machine activity for human activity (substitution myth, see [92]). Empirical data on the relationship of people and technology suggest that this is not the case and that traditional automation has many negative performance and safety consequences associated with it stemming from the human out-of-the-loop (OOL) performance problem (see [22], [50]).

Classically, the out-of-the-loop performance problem leaves operators of automated systems handicapped in their ability to take over manual operations in the event of automation failure [22]. The OOL performance problem has been attributed to a number of underlying factors, including human vigilance decrements (see [7], [86]), complacency (see [63], [68], [86]) and loss of operator situation awareness (SA) (see [15], [21], [22]). Cognitive engineering literature has discussed at length the origins of vigilance decrements (e.g., low signal rates, lack of operator sensitivity to signals), complacency (e.g., over trust in highly reliable computer control) and the decrease in SA (use of more passive rather than active processing and the differences in the type of feedback provided) in automated system supervision and has established associations between these human information processing shortcomings and performance problems. However, though all of these undoubtedly play an important role in the out-of-the-loop performance problem, we consider that these different factors have masked a preliminary question: what is the difference between action resulting from my intention, beliefs or desires and others' action or involuntary action? What is the difference between being an agent or not? What is the difference between supervisors in control and complacent supervisors? Our belief is that the investigation of the agency mechanism may be fruitful in the comprehension of the OOL performance problem.

An aeronautical problem: feeling of control in automated systems

A possible interpretative framework on the nature of the transformation induced by the automation can be tracked back to the agency mechanism, that is, the feeling of being causally involved in an action (the sense of agency, [30]). This hypothesis is echoed by the claim of Baron when he states:

"***Perhaps the major human factor concern of pilots in regard to the introduction of automation is that, under some circumstances, operations with such aids may raise the critical question, who is in control now, the human or the machine?***" [4]

This is not a simple question and it is certainly not merely a matter of the pilots' self-esteem being threatened by the advance of the machine age. "The question goes to the very heart of the nature of piloting, the seemingly divided authority between human and machine and, mainly, what is the role of the pilot as minder of equipment that is not only increasingly sophisticated, but also increasingly autonomous" ([86], p.452). The concern is legitimate. The interposition of more and more automation between the pilot and the vehicle tends to distance pilots from many details of the operation. They are isolated from most of the physical structures of the aircraft. At the same time, the automation tends to isolate the crew from the operation of the aircraft, because the automatic equipment monitors and controls it, providing little or no trace of its operations to the crew, isolating them from the moment-to-moment activities of the aircraft and of the controls [62]. This combination of relative physical and mental isolation from the basics of flying helps to contribute to a decreased feeling of control by the pilots. At the extreme, some pilots argue that automation reduces the status of the human to a "button pusher" [87] describes those who build automated systems as "trying to take humans out of the loop". How to design systems to allow the crew to remain an intentional agent (i.e., "in the loop") is a crucial question, but is also an extremely difficult problem.

To solve this question, it is necessary to understand how automation influences the humans who work with it and how humans feel about action control. However, few studies in the aviation domain have investigated this question. In contrast, the mechanism of self-attribution has enjoyed particular interest in the fields of social psychology, movement science and neuroscience. This area of research is well-known as the science of agency (see [31]).

Agency: state of the art

When we act, we usually feel ourselves controlling our own action and causing the accompanying action–effect. This experience of oneself as the agent of one's own actions has been described as "the sense of agency" [30].

One way to get at the concept of the sense of agency is to distinguish it from the sense of ownership for movement [30]:

- Sense of ownership: the pre-reflective experience or sense that I am the subject of the movement (e.g. a kinesthetic experience of movement).
- Sense of agency: the pre-reflective experience or sense that I am the cause or author of the movement (e.g. an experience that I am in control of my action).

Though agency refers to the sense of intending and executing actions, body ownership only refers to the sense that one's own body is the source of sensations. Although in the normal experience of willed action the self-agency and the sense of self-ownership coincide and appear indistinguishable, both may be partly independent and have different processes by which each of them is constructed. It is possible to say that I am moving and therefore that it is my movement, and thus have a sense of ownership for it, in cases where there is no sense of agency for the movement, for example in reflex or involuntary movements.

Interesting example of such dissociation is proposed by Penfield's classic finding on movements induced through electrical stimulation of the motor cortex [64]. Conscious patients were prompted by stimulation of the exposed brain to produce movements that were not simple reflexes and instead appeared to be complex, multi-staged and voluntary. Yet, their common report of the experience was that they did not "do" the action and instead felt that Penfield had "pulled it out" of them. This observation only makes sense if we consider that sense of ownership for an action ("my arm is moving") does not suffice for recognizing oneself as agent of this action ("I voluntary move my arm"). This asymmetry suggests that agency and ownership may have different processes by which each of them is constructed and should have different effects on awareness of the body. Therefore, we can raise the following question: what must be added to be able to self-ascribe a movement ("I am moving")?

Sense of agency: different approaches

Most people can readily sort many events in the world into those that they have authored and those that they have not. This observation suggests that each person has a system for authorship processing [80], a set of mental processes that monitors indications of authorship to judge whether an event, action, or thought should be ascribed to self as a causal agent (see [35], [48], [81]). However, these mental processes are not clear at the moment.

In recent years, laboratory studies have attempted to shed more light on this mechanism. Empirical data in recent psychology (e.g., [1], [20], [23], [45], [60], [67]), in psychopathology (e.g., [27], [28],

[71]) and in neuroscience (e.g., [9], [18], [26], [74], [75]) have been accumulated and two different approaches have emerged.

The ***"bottom-up" approach*** considers that the higher-order attributions of agency may depend on the first-order experience of agency [31]. In this case, authorship is a given, a kind of knowledge that arises in the very process whereby actions are produced. Authorship processing seems inherent in the way the action is produced (for an original illustration, see box 1). However, several works suggest that action and agency do not always properly coincide. Clinical evidence, such as the "***Alien hand syndrome***" [36] or schizophrenic syndromes (see [9], [11], [29], [69]), neuropsychological evidence (see [34], [42], [43], [53]) and works on automatism (see [2], [3], [70], [77]) show that the sense of agency is fallible. For example, the priming studies imply that the sense of agency may even occur in situations in which the participant plays no objective role in bringing about the outcome. In a "shelping hands" pantomime task (see figure 1), subjects experienced high degrees of agency for movements that were in fact performed by another agent, when only the other agent's hands appeared in the place where subjects' hands would normally appear and when subjects could hear instructions previewing each movement [81] (see also the rubber hand illusion, [12]). If so, we must accept that authorship identification needs processing which is separate from the mechanistic process of real mental causation.

In order to transcend these limits, the ***"top-down" approach*** considers that our conscious awareness of action is subserved by an inferential process (e.g. [19], [39], [71], [78], [79], and [82]). As pointed out by Wegner ([77] p. 218), "we are not intrinsically informed of our own authorship" and instead, we use sensory evidence to "make sense" of our actions and their antecedent/subsequent events. In other words, the inferential process would generate the experience of action by accumulating sensory evidence about actions in the same way that other perceptual/inferential processes rely on sensory evidence about external events. An interesting illustration of the top-down approach has been proposed by Wegner ([77], [82]).

The early insight of Hume in A Treatise on Human Nature [44] was that the "constant union" and "inference of the mind" that underlies the perception of causality between physical events must also give rise to perceived causality in "actions of the mind".

Drawing on this idea, the theory of apparent mental causation ([77], [82]) suggests that the experience we have of causing our own actions arises whenever we draw a causal inference linking our thought to our action. This inference occurs in accordance with principles that follow from research on cause perception and attribution (see [24], [38], [55], [56]) – principles of priority, consistency, and exclusivity. [82] argues that, when a thought occurs prior to an action, is consistent with the action and the action has no plausible alternative cause, then we experience the feeling of consciously willing the action. In contrast, when thoughts do not arise with such priority, consistency and exclusivity, we experience the ensuing actions as less willed or voluntary.

Box 1 - Why can't you tickle yourself? Sense of agency illustrated

Researchers have increasingly studied how we can distinguish between sensations that are produced by our own movements and sensations that are caused by a change in the environment ([14]; [47]; [88]; [89]). These studies have repeatedly demonstrated that the sensory consequences of self-generated movements are perceived differently than identical sensory inputs that generated externally. In particular, there is now substantial evidence that the sensory effects of self-produced movement are attenuated (see for example [11]).

A recent study by Blakemore and collaborators [10] is relevant in this context. Using a robotic interface, delays of 100, 200 and 300 ms and trajectory rotations of 30", 60" and 90" were introduced between the movement of the left hand and the resultant tactile stimulation on the right palm. Increase in temporal and spatial discrepancies between the subject's movement and the resultant tactile stimulation make it possible to differentiate between the perception of self-produced sensation (no delays and no trajectory rotations) and the perception of externally produced sensation. Participants were asked to rate the tactile stimulus in terms of several sensations, including tickliness (painful, intense, pleasant, irritating, and tickly). Interestingly, the authors observed a systematic increase in the sensation experienced as the discrepancy between the applied movement and the felt movement increased in time or space. In other words, conscious experience of being tickled is highly dependent on the source of the action.

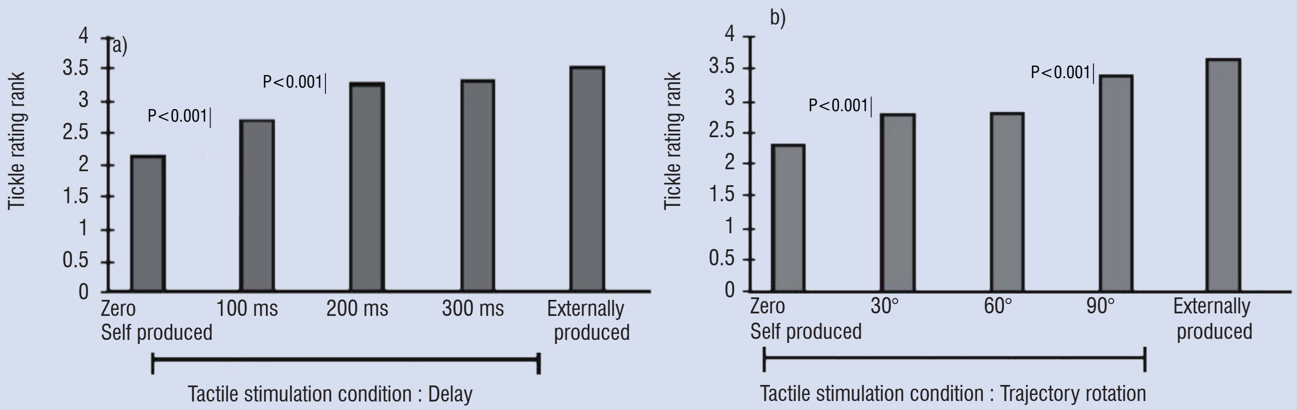

Figure B1-01- Graph to show that the tickliness of a tactile stimulus increases with increasing delay (a) and trajectory rotation (b) between the movement of the left hand and the tactile stimulus on the right palm. Reproduced from [10].

Figure 1 - Experimental paradigm used by [81]: a participant viewed from the front, as she would see herself in the mirror (on left), and participant with hand helper as viewed from the side (on right). Participants watch themselves in a mirror while another person behind them, hidden from view, extended hands forward on each side where participants' hands would normally appear and performed a series of movements. When participants could hear instructions previewing the movements, their sense of agency for these movements was enhanced, but such vicarious agency was not felt when the instructions followed the movements. Reproduced from [81].

Evidence from several experiments has accumulated in relation to this theory. For example, Gibson and collaborators [37] asked participants to type letters randomly at a computer keyboard without seeing the screen. They were told that the experiment examined "automated typing" and that their random responses would be analyzed. Just before this, participants were exposed to the word deer in an ostensibly unrelated task. Then "the automatic typing" began and participants typed for 5 minutes. The experimenter ostensibly ran a program on the typed text to extract the words that had been typed, and then asked participants to rate words to indicate the degree to which they felt they had authored that word. None of the words rated were actually produced, yet participants reported higher authorship ratings for the word they had seen in the prior computer task (deer) relative to other words. This finding suggests that people can experience will for an action that was never performed, merely when they have prior thoughts consistent with the action (see also [1]).

Because human agents have access to a variety of sources of information about authorship (e.g., one's own thoughts, interoceptive sensations, external feedback, etc.), the identification of authorship indicators involved in the authorship processing becomes a first concern. Several indicators have been already proposed, including body

Box 2 - Wegner principle in an aeronautical context: a first attempt

Recently, we have proposed a preliminary experiment, addressing the effect of automation over the feeling of agency in a simulated control task involving authority sharing with a robot [6]. The experiment consisted in controlling a robot moving on a plane in a 2D video game. The task of the participants was to bring the robot to the target, while avoiding various obstacles. The robot was semi-automated and designed to avoid the obstacles by itself and go to the target. If the participant considered that its behaviour was not optimal, he could operate on two parameters: robot velocity, and robot direction. Latency (the time before considering operator command, 400 ms or 1000 ms), Level of Authority (the level of authority assigned to the operator, 30 %, 50 % or 70 %) and Feedback (presence of feedback about the command sent by the automatism with direction, velocity and detection signal) were manipulated and the role of these different factors on performance and feeling of control was measured. The main results showed that (1) the feeling of control depends both on the level of operator authority and on the performance obtained in the task, (2) the latency had no effect on the feeling of control and (3) the presence of feedback about an automatism's intention does not influence the feeling of control.

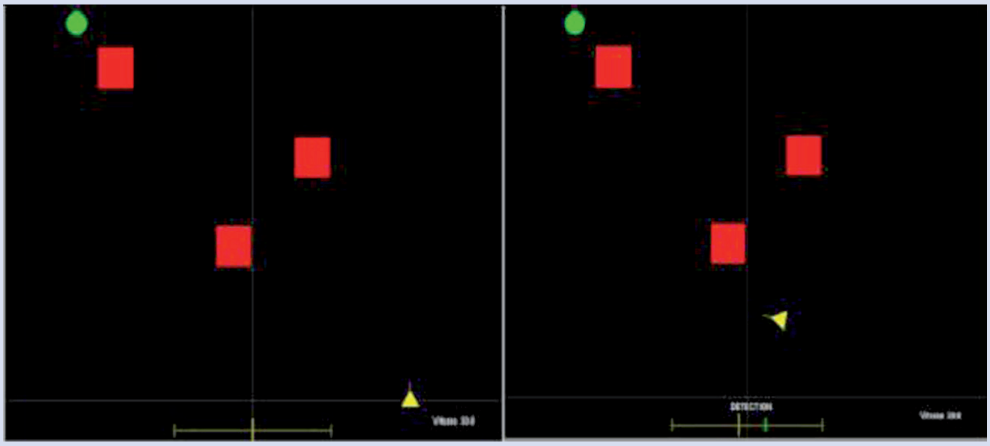

Figure B2-01 - Experimental paradigm used by [6]. The experiment consists in controlling a robot moving on a plane in a 2D video game. The visual scene (see figure 1) was composed of: one semi-automated robot represented by a yellow triangle with an arrow marking the displacement direction, one target represented by a green circle and three obstacles represented by red squares. The task of the participants was to bring the robot to the target, while avoiding the obstacles. Reproduced from [6].

These results were discussed in regard to the three principles enounced by Wegner –principles of priority, consistency and exclusivity. Even though further studies are clearly needed to make progress on this issue, this first experiment shows the importance of the concept of agency in the question of human-automation coupling, its ability to be assessed by a participant's judgment and its usefulness to understand the factors enabling a feeling of control even in a supervisory task.

and environment orientation cues (e.g., [76]), direct bodily feedback (e.g., [32]; [35]), direct bodily feedforward (e.g., [8]; [9]), visual and other indirect sensory feedback (e.g., [17]; [61]), social cues (e.g., [51]; [57]), agent goal information (e.g., [52]) and own behavior-relevant thought (e.g., [77]; [78]; [82]). In our mind, the investigation of such indicators in supervisory tasks could improve our comprehension of the OOL performance problem significantly (for a first attempt, see box 2).

Agency measurement

A second important question relates to the measurement of this sense of agency. The sense of agency has proved difficult to quantify. Historically, philosophical and psychological approaches to the agency have focused on the mechanism of self-attribution or, in other words, one's ability to refer to oneself as the author of one's own actions (for reviews, see [19]; [30]). These involve participants introspecting upon his or her sense of agency by answering questions such as ''Did you do that?" In particular, previous studies of priming (e.g. [1]; [82]) used explicit judgments to measure the sense of agency. A significant number of theorists have argued that the introspective report is the only legitimate marker of agency in any context. Where a creature is unable to produce introspective reports of any kind, then we have no reason to think that there is a sense of agency. However, [72] recently highlighted the distinction between the feeling of agency, as captured by implicit measures, and explicit judgments of agency. In particular, we can distinguish two different aspects of the self the 'narrative' self and the 'minimal' self [30]. The narrative self corresponds to "a more or less coherent self (or self-image) that is constituted by a past and a future in the various stories that we and others tell about ourselves" ([30], p. 15). Clearly, introspective reports deal with this first aspect of the self. The minimal self, on the other hand, corresponds to a more primitive and embodied sense of self.

It is the pre-reflective feeling that a given movement is performed by me, or that a given experience is had by me. This reference to self is distinguished from the autobiographical sense of having a narrative self that persists across experiences. The minimal self is more like an instantaneous feeling of "mineness", with which experiences are labeled. As suggested by Gallagher [30], this aspect of the self depends on an ecologically embedded body, but one does not have to know or be aware of this to have an experience that still counts as a self-experience. In other words, the minimal self cannot be reduced to self-attribution reports. In this context, we have to make a distinction between the fact that I own a certain mental or bodily state and the fact that I recognize this state as mine (see also, [14]).

From a conceptual, a phenomenological and an empirical point of view, the relations between a minimal or core self and an extended, narrative, or autobiographical self remain controversial (for a general discussion about the relationship between implicit measure and verbal report, see [40]. They may be seen to be complementary notions. But is the core self a (logical and temporal) precondition for the extended (narrative or autobiographical) self? Or is the core self, on the contrary, a subsequent abstraction; is it simply a stripped-down version of what must count as the genuine and original self [94]? To resolve this question, the study of the self needs to go further than the simple use of attribution judgments and to explore the possible dissociations between the minimal and the narrative self in change detection. In particular, if the minimal self is a precondition for the narrative self and could exist in absence of self-attribution reports, explicit judgment tasks are no longer sufficient and it becomes a key concern to find an implicit measure of agency, — one that is sensitive to the minimal self. In our mind, the identification of accurate agency markers is essential if the science of agency is to have any chance of success. Intentional binding appears as a good candidate for such implicit measurement.

Intentional binding as an implicit measurement of agency

Time appears as a first concern regarding the sense of agency. Two key findings have placed linkage across time at the heart of this approach. First, the mental representation of the action predicts the later effect ([25]; [46]). Second, the strength of association, and thus the feeling of agency, operates over a limited time window. As the interval between an action and its sensory effect increases, subjects become less likely to agree that they caused the sensory effect [82].

If the temporal contiguity between one's action and the resultant effects is central to the sense of agency ([77], [79], [93]), the reverse seems also true: being an agent of an event may affect the perceived time of such an event. Particularly, recent research has shown that human intentional action is associated with systematic changes in time perception: The interval between a voluntary action and an outcome is perceived as shorter than the interval between a physically similar involuntary movement and an outcome.

In an experiment based on Libet's time judgment paradigm [54], Haggard and collaborators [43] asked participants to press a key, which produced an auditory stimulus a short interval afterwards. Participants were supposed to estimate, in separate blocks, the time of either when they made the action or when they heard the tone, by referring to a rotating clock hand. The main results showed a temporal attraction between action and effect (actions are perceived as shifted forward in time towards the effects that they produce, while the effects of intentional actions are perceived as shifted backwards in time towards the actions that produced them) in case of intentional action (see figure 2). In contrast, involuntary movements (movement resulting from transcranial magnetic stimulation) show a perceptual repulsion. This ''intentional binding" effect [43] is taken to be a measure of the sense of agency, because the binding between voluntary actions and effects reliably occurs in situations in which the participant is an agent relative to non-agency situations such as passive movement.

Based on this preliminary work (see also [41]), several studies have explored the necessary and sufficient conditions of temporal binding. [43] again highlighted the centrality of intentions for temporal binding and showed that temporal binding depends on the predictability and temporal proximity of the effect. They found larger perceptual shifts for fixed than for randomized movement–effect intervals. Additionally, short intervals yielded larger perceptual shifts than long intervals. More recently, several studies have confirmed the effect of the statistical relation between events on the binding effect ([58]; [59]), which is generally thought relevant to the perception of causation [49]. Temporal binding also depends on the physical characteristics of the effect: The more salient an auditory effect, the stronger the temporal binding of the movement to the effect [90]. Furthermore, temporal binding is not limited to the perception of self-generated movements, but is also found in the observation of other human agents, as opposed to non-biological agents [91]. Similarly, passive movements of the participant's body are less bound to their effects than actively initiated ones ([73], [90]). Thus, temporal binding has been described as an associative mechanism that is specific to intentional action. However, recent research has shown that intentional action is not sufficient to produce temporal binding and has confirmed that causality is the critical trigger [13]. At the same time, several studies have shown that intentional binding also depends on external sensory evidence regarding the source of the action. For example, using prime in order to modify the content of conscious thought prior to moving, Moore and collaborators [60] show that general inferences about external events could modulate the perceived interval between action and effect for involuntary movements.

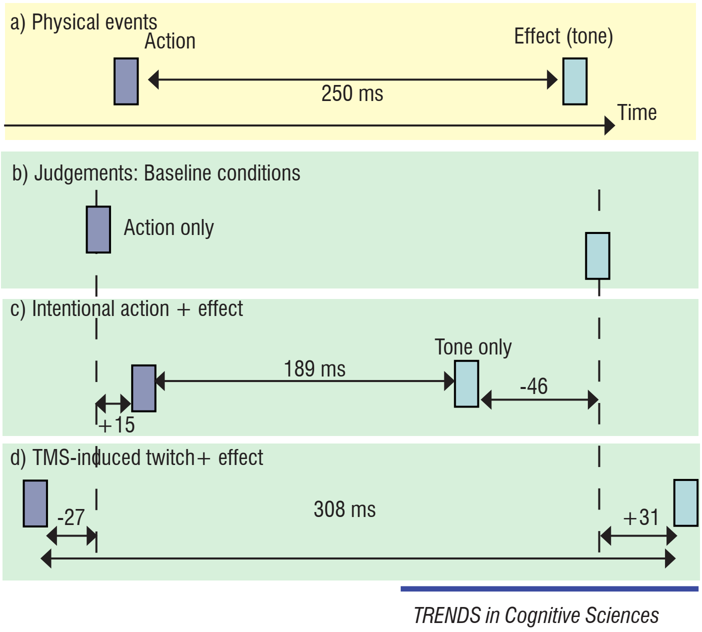

Figure 2 - Intentional binding between voluntary actions and their effects.
(a) Subjects make voluntary action to evoke a tone 250 ms later.
(b) The perceived time of action and tone are first estimated in baseline conditions in which only the action or the tone occurs.
(c) When action and tone occur together, the perceived time of the action shifts forwards in time from the baseline value, towards the tone. The perceived time of the tone shifts earlier in time, towards the action. Action and tone are bound together across time, implying a reduction in the perceived interval between them.
(d) Replacing the intentional action with a physically similar involuntary movement evoked by TMS abolishes and reverses the binding effect.
Data from [43].

Though several questions remain concerning the necessary and sufficient conditions of temporal binding, we could assume that this phenomenon offers a robust measurement of the sense of agency. This has been shown with a variety of methods over a considerable interval range, ([16]; [20]; [23]; [45]; [60]; [83]; [84]). Our concern in the following part of this article is the possibility of using this implicit agency measurement in the comprehension of the OOL performance problem.

Intentional binding: a window on to OOL performance problem?

In the first part of this review, we have proposed that the mechanism of agency be considered as a potential origin for the OOL performance problem. Interactions with complex machinery are clearly one area where sense of agency is important, but may be difficult to achieve. In regard to the large body of research concerning the intentional binding effect, this phenomenon appears as a good candidate to tackle such a relation. However, some issues and problems must be addressed, in order to generalize intentional binding for a more complex situation, like the situations encountered in an aeronautical context.

First, how robust is the binding effect? Specifically, the problem is to determine whether an intentional binding effect could be extended to more complex situations. Indeed, nearly all previous investigations have based their methods on a very simple paradigm, typically asking participants to press a key and judge either the time of their key-pressing or a subsequent tone. Few or none (excepted [20]) have studied how binding occurs for the kinds of actions performed and events encountered in everyday life, such as kicking a ball and watching it fly away, in such a way that the external validity of this effect remains unclear. Particularly, interactions with machines regularly involve sending a command to a system and monitoring the system response, and we regularly feel a sense of controlling how the machine behaves in such situations. Under such a condition, we can require the robustness of the binding effect for this more demanding task and with a more complicated device that most experimenters use to find such nuanced psycho physical effects.

Secondly, how gradual is the binding effect? The gradual nature of the binding effect, particularly the role of action selection in binding, has been poorly explored at the moment. Indeed, previous tasks relied either on explicit binary judgments of agency vs. non-agency in self-other discrimination paradigms [17], or on contrasting binding between entirely voluntary and entirely involuntary situations [43]. In such a case, the intentional binding is viewed as an all-or-none phenomenon. Such a view of the binding effect is not suited to the real nature of agency in a multi-agent environment. For example, agency comes by degrees: one can feel more or less in control. This variation is particularly clear when using machines. The feeling of control varies quite subtly as the relation between operator inputs and machine response. Whether or not the binding effect is sensitive to this gradual component of agency is an important issue in regard to the use of this phenomenon in more complex situations.

Thirdly, the temporal range in which binding operates remains ambiguous. Early studies on binding showed that longer action–outcome intervals were associated with reduced binding ([41]; [43]; [20]). Authors concluded that the strength of association operates over a limited time window and intentional binding is limited to sensorimotor timescales. Clearly, such a timescale does not match with the complex nature of the actions and their effects in an aeronautical context. The possibility to find intentional binding for larger intervals becomes a first concern. Recent works have already discussed the presence of binding for large intervals, as well as the increase of binding with time (for a discussion see [45]; [84]). Using a magnitude estimation procedure, more recent work by Buehner and Humphreys [13] has shown that temporal binding occurs over intervals far greater than those previously explored (up to 4s). Interestingly, they showed that this temporal binding effect increased with interval size and that initial binding limitation in time only depends on the artificial constraints of the Libet Clock method. How can we reconcile these inconsistent results? What we propose, is to go further than the classical acceptance that temporal contiguity is an important factor for the sense of agency (see [43]; [79]). Temporal contiguity is certainly a key factor for the sense of control, but this contiguity must be considered in regard to the temporality of the task carried out. As explained by Wegner [77], causal events precede their effects, usually in a timely manner. To be perceived as a truly worthy cause, the event can't start too soon or start too late - it must be on time just before the effect. In other words, we propose that temporal contiguity is task-dependent and that intentional binding occurs in a specific "window of opportunity", which may vary across tasks and may also depend on the range of action-effect delays experienced in a given setting. For example, operant learning is similarly sensitive to the natural time delays of the system linking actions to effects, even for systems as familiar as one's own body. Particularly, when rats learn to avoid eating food associated with illness, the optimal delay between eating and illness is not the shortest possible delay, but rather a delay consistent with their normal digestive operation [33].

Accordingly, in a recent and original experiment [5], we investigated intentional binding in a complex naturalistic situation (see box 3). It is noteworthy that the temporal judgment effects were found despite the demanding nature of the task and despite the fact that the complicated simulator is not the kind of device that most experimenters use to find such nuanced psychophysical effects. That the temporal judgments were observed is a testament to the robustness of the phenomenon of intentional binding. This initial study provides interesting perspectives as it asks many questions.

A fertile way of investigation

In the current context of a continued increase in automation, the OOL performance problem becomes a major human factor question. In this review, I have tried to show that psychological ideas about the self, and particularly the concept of agency, can help to understand the performance problem. Our first studies about the agency mechanism in supervision tasks involving highly automated systems clearly show the relationship between automation and a feeling of control. However, more research is needed to fully understand the role of the sense of agency in the OOL performance problem.

Relation between sense of control and operator performance

The next step would be to test whether systems that produce a stronger subjective sense of agency also produce better performance. When we get on an airplane, we believe (and hope!) that the pilot feels in control of the aircraft. Interestingly, in the case of a high

Box 3 - Intentional binding in aeronautical context: a first trial

In a recent study [5], we have decided to explore intentional binding in a complex naturalistic situation involving flying an aircraft with various degrees of autopilot assistance. Particularly, we assessed the influence of the level of automation on participants' jugement of agency, as well as on intentional binding.

Important results were obtained:

- **replication** of the basic binding effect **in a more complex situation** (with high face-validity);
- quantitative changes in **binding** are **strongly associated** with quantitative changes in **explicit reports** of agency;
- **a Gradual** increase in the interval estimates with the in creasing level of automation;
- Iintentional binding occurs in a specific **"window of opportunity"**, which depends on the range of action-effect delays experienced in a given setting.

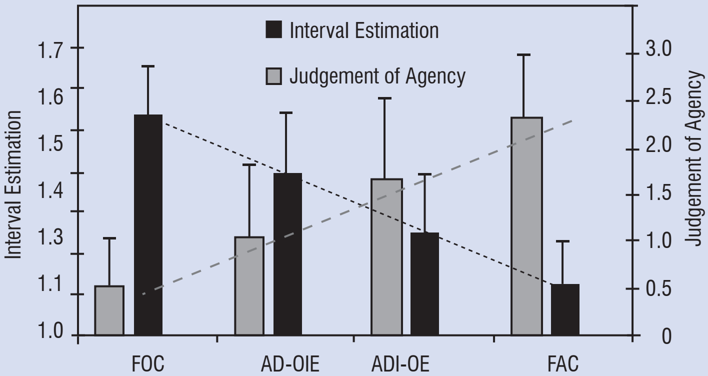

Figure B3-01 - Modulation of interval estimates (in gray) and explicit judgment of agency (in black) by automation level. The gradual increase in automation (from left to right) comes with a gradual increase in interval estimation (decrease in the binding effect) and a gradual decrease in the feeling of agency. Reproduced from [5].

This research presents additional compelling evidence for the existence of the binding effect in a new paradigm that is substantially more ecologically-valid than the traditional laboratory paradigms that have been used to asses intentional binding. It is noteworthy that this binding effect was found despite the demanding nature of the task and despite the fact that the complicated simulator is not the kind of device that most experimenters use to find such nuanced psychophysical effects. Such a result bears witness to the robustness of the intentional binding phenomenon.

Our findings are important, not just for theories regarding the special nature of voluntary action in the mind/brain but for the improvement of the interactions between humans and machines. Human welfare depends increasingly more on the successful interaction between humans and machines, as is obvious in the cockpit of any commercial airplane. Intentional binding may be a useful measure in the understanding and optimization of this interaction.

level of automation, pilots have reported increased problems in understanding and anticipating aircraft behavior, and in tasks such as programming the FMS [65]. For instance, automation surprises [66] arise when the technology autonomously performs tasks that cause the aircraft to behave in a manner that the pilots had not anticipated. We assume that such a decrease in situation awareness arises from a non-satisfaction of the agency mechanism. How does agency influence the operator performance? How does agency modulate the consciousness threshold? Many questions remain unclear concerning the relationship between agency and performance, and further studies are needed.

How can the operators' sense of control be modulated in a highly automated system?

Another important issue concerns the psychological factors underlying the feeling of control. Indeed, the research of factors affecting the feeling of control of the operator could lead to interesting design principles offering the maximal agency. According to [78], the feeling of control seems to occur in accordance with various principles– priority, consistency and exclusivity. Indeed, Wegner argues that when a thought occurs prior to an action, is consistent with the action and the action has no plausible alternative cause, then we experience the feeling of consciously willing the action. In contrast, when thoughts do not arise with such priority, consistency and exclusivity, we experience the ensuing actions as less willed or voluntary. We believe that these principles could be an interesting way to artificially modulate the feeling of control of an operator in interaction with highly automated systems. The investigation of this authorship processing in the field of human-machine interaction may be fruitful. Indeed, different solutions may be envisaged when designing a human-machine interface (HMI). In our opinion, such design decisions should be based on a precise understanding of the effects of key design variables (e.g. level of automation, command & control devices, modalities of the feedback) and of the mechanisms involved in authority sharing.

Binding effect: a new tool for HMI evaluation

To conclude, we assume that this topic of research will lead to the creation of technologies that inspire new ways of working. The ability to measure the sense of agency quantitatively is important, since it allows the sense of agency to be used as a measure in evaluating human-automation performance. We think that such works will lead to the introduction of a new methodology for the specification and evaluation of the potentiality for an HMI to satisfy the agency mechanism, and by extension, to keep the operator in the loop. New progress in HMI optimization should follow. We also believe that this new methodology could be used in the evaluation of the immersive quality of a virtual environment. In a simulated environment, the operator needs to feel in control of the simulated action. We assume that the intentional binding effect could quantify this immersive quality of the simulator ■

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Acronyms

SA (Situation Awareness)
OOL (Out-Of-the-Loop)
HMI (Human Machine Interface)
FMS (Flight Management System)

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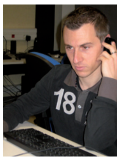

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Formal Verification of Critical Aerospace Software

Embedded software is implementing more and more functions in aerospace, including critical ones. Model Driven Engineering has changed software life cycle development by introducing models in the early steps of software development. Verification and validation is essential, at model and at code levels, and still mostly done by simulation and test. However, formal methods, which are based on the analysis of the program or software model, are being transferred to industry for verification of critical software. This paper presents the context of aerospace software development, a brief overview of formal methods and of the associated industrial practice, and the work done at Onera on formal verification of critical Aerospace software at model and at code levels. This work addresses four themes:

- Specifics of application of formal methods to aerospace;
- Model driven engineering at platform level;
- Cooperation of analysis techniques;
- Automating test using formal methods.

Each of these four themes is a research domain in itself; it is thus impossible in a single paper to provide a detailed state of the art and an exhaustive list of research challenges for each of them. This paper rather aims at giving a broad vision and at presenting work done at Onera in these domains.

Aerospace context

Aerospace systems have experienced significant and continual evolution over the last 30 years. Digital technologies have become more mature, reliable and efficient and have been introduced inside aircraft for the implementation of more and more functions, including critical ones, as shown in figure 1.

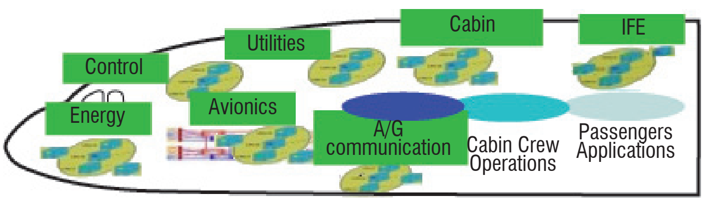

Figure 1 - Embedded functions

Software is essential in the implementation of these functions. For example, the avionics systems in the Airbus A380 include more than 100 millions lines of code. Figure 2 gives an idea of the evolution of the volume of embedded software.

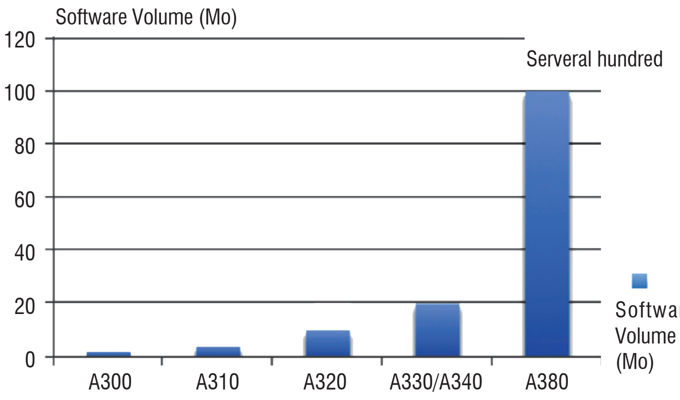

Figure 2 - Evolution of the volume of embedded software

The same thing is happening in the space domain; the number of embedded computers is still much smaller than in aeronautics, but it is growing and will continue to do so. In addition to control functions, satellites and spacecrafts now embed complex management functions (mode management, load, communication, etc). Some functions are critical, such as the one responsible for docking to the space station in the ATV (Automated Transfer Vehicle).

Software engineering

In this context, special attention must be given to software engineering in order to master software complexity and ensure the correct execution of software executing critical functions. Classically, software development is decomposed into several steps: requirements, design, coding and verification and validation (essentially by test, unit test and integration test), as represented on figure 3.a.

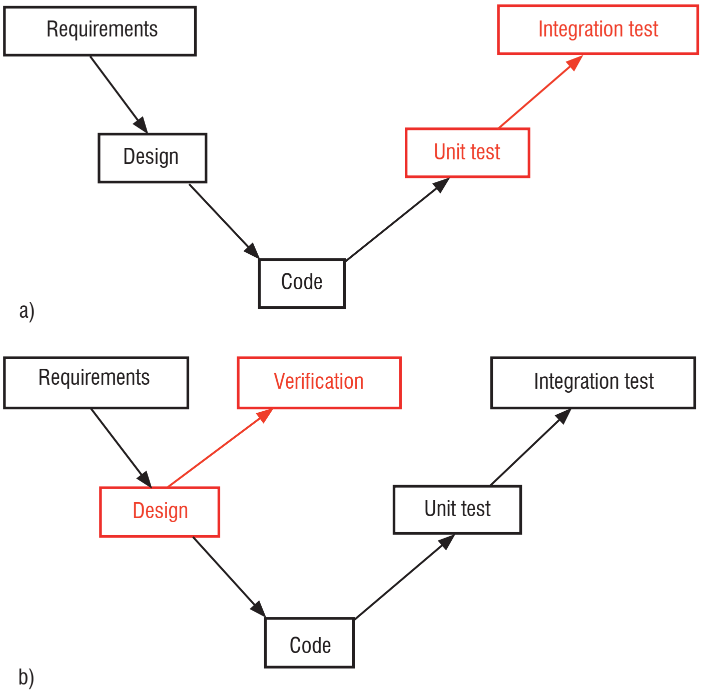

Figure 3 - a) Classical software development cycle / b) MDE software development cycle

Verification and validation is an essential step for critical software and represents more than 50% of software development costs. Another important rule is that the later an error is detected, the more costly it is to correct it [1].

This is one of the main reasons for the advent of Model Driven Engineering (MDE) in software development. In traditional software development, the reference is the code. In MDE, the reference is a model that is developed before the code (and from which the code can in some cases be automatically generated). This model can be simulated and thus verified against requirements. If the code generator is qualified, unit test can be removed and replaced by verification on the model.

Verification and validation means

Software verification and validation is still mainly achieved by means of simulation and testing. However, these methods are not exhaustive, and still very labor-intensive and costly. They may also reach the limits for specific verification objectives. Alternative techniques exist and are being transferred: formal methods [2]. These methods do not require execution of the software and are based on mathematical analysis of the code or the model. They have the advantage of being automated and exhaustive. Onera has chosen formal methods for the verification of critical aerospace software.

Formal methods

A formal method is defined by a formal notation together with a formal analysis technique (definition taken from [3]). A notation is formal if it has non-ambiguous, mathematically defined syntax and semantics. The formal analysis technique then allows automated computation of properties of systems modeled using the formal notation.

Brief overview of existing techniques

The first work on formal methods dates back to the 60's with Hoare logic, to prove the correctness of programs [8], [9]. Many different formal notations and analysis techniques have been defined. Our goal here is not to give a detailed state of the art report, we refer the reader to the formal methods wiki (http://www.formalmethods.wikia.com) which gives many references. Formal notations can be broken down into programming languages, formal modeling languages that are usually dedicated to a specific type of application (such as synchronous languages for reactive systems) and formal notations for the expression of properties (such as temporal logics).

Analysis techniques are typically presented under three categories [3]: model checking, deductive techniques and abstract interpretation, even if the borders between techniques are not as strict as they used to be. Model checking explores all possible behaviors of a formal model to determine whether a specified property is satisfied. Deductive methods involve mathematical arguments, such as mathematical proofs, to establish a specified property of a formal model. Abstract interpretation is a theory for formally constructing conservative representations of the semantics of programming languages.

State of industrial practice

Formal models are now used in different application domains [4], [6] e.g. the SCADE language is used for the design of command and control systems in aerospace. Automated code generation from models is also common. There are an increasing number of industrial experiments on the application of formal analysis techniques to the verification of software. Model checking is beginning to be used operationally in the railway domain, where correct-by-construction approaches based on B have been used for several years now e.g. for the development of the control software for the Paris metro [7]. Certification credits for the use of formal methods in aeronautics have been obtained by Airbus for the A380 software [13], [14]. Rockwell Collins has been using model checking for the validation of requirements [12], [11]. Early on, NASA was investigating the use of formal methods for the certification of critical systems [5] and has several research teams working on formal verification (Robust Software engineering at Ames, Langley; Formal methods, Laboratory for Reliable Software at JPL).

Onera work

Onera work in formal verification of software has been around four themes:

- Specifics of application of formal methods to Aerospace (methodological work to integrate these new verification means into industrial processes while taking into account certification constraints);

- Model driven engineering at platform level;
- Cooperation of analysis techniques;
- Test automation using formal methods.

Specifics of application of formal methods to Aerospace

Certification is a structuring constraint in aeronautics. The certification standard for software is DO-178B/ED-12B. This standard does not prescribe a specific development process but identifies four processes in the software development cycle: the requirement process producing High Level Requirements (HLR) from System Requirements; the Design process producing Low Level Requirements (LLR) and software architecture from HLR; the coding process producing source code from software architecture and LLR; the integration process producing executable object code from source code. DO-178B identifies verification objectives for each of the four processes, as synthesized on figure 4.

Version B of DO-178 was released in 1992 and software development has changed significantly since then. So EUROCAE and RTCA decided to prepare an update of the standard in 2005. DO-178C was released in December 2011 and proposes, in addition to the core document, four technical supplements addressing qualification of tools, object-oriented technologies, model-based design and formal methods. Onera has been active in the writing of the formal methods supplement [3]. This document explains how formal methods can be used for the verification of certified software and proposes adapted verification objectives taking into account the differences with classical verification techniques such as testing. A summary presentation of this supplement can be found in [15].

This work on certification standards is essential to be able to transfer formal methods to industrial practice, as is the work on methods that Onera is doing in collaboration with industrial partners such as Airbus. Having an appropriate formal notation and an efficient analysis technique is necessary but absolutely not sufficient to be able to take advantage of all the benefits of these new verification methods. Methodological work is mandatory and includes the identification of the requirements that can be verified formally, their formalization and the definition of specific verification strategies for the software in question. Onera has been working with Airbus on these aspects at both model and code levels [17], [10], [13].

This methodological work may reveal needs for new techniques, to complement formal analysis. For example, when working on the definition of a method to apply model checking to SCADE models, we noted that a lot of time was spent on the understanding of the counter-examples provided by the model checker. We proposed an automated technique and an associated tool to extract from the counter examples the meaningful information and present it to the user in a comprehensible way [16].

Model Driven Engineering at platform level

The anticipated spectrum of applications of model driven engineering in aerospace embedded systems design is not restricted to critical flight control software. Indeed, MDE approaches can be used at different conceptual design levels, from aircraft level to platform level down to software components level.

Onera has ongoing projects to support the design of embedded platforms through model driven approaches. In their current state, platform models are dedicated to the study of performance or dysfunctional aspects (or even other non-functional aspects such as electrical consumption or weight). Models help in the formalizing of the different components and architectural concepts around which the execution platform is built, as well as attributes according to which the performances and safety of the platform are assessed. In such models the properties capturing resource allocation requirements and safety related requirements can be formally expressed and automatic tools such as SAT, Pseudo-Boolean or SMT solvers can be used either to verify manual designs or to generate correct-by-construction resource allocations or platform configurations.

In addition, model based specifications can valuably subsume natural language specifications, not only in the design process, but also in the procurement process between contractors and sub-contractors. Models may in the near future become critical assets on which the whole system design process will rely.

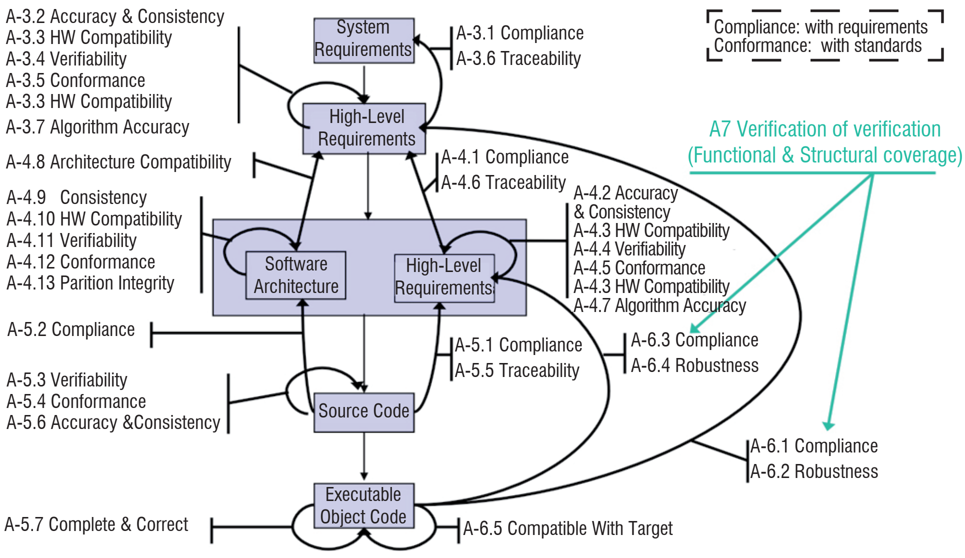

Figure 4 - DO-178B verification objectives.

A remarkable indication of this trend is the Topcased software suite [www.topcased.org], an open-source, Eclipse-based Integrated Development Environment dedicated to embedded systems applications. Onera was involved in the original Topcased project, and is now involved in its successor project OPEES [www.opees.org]. Onera contributions to OPEES consist in providing a theoretical framework, tools and associated methodologies to enable formal verification and automatic model synthesis for users of MDE processes.

Meta-models and semantics

Meta modeling proceeds by defining class diagrams (e.g. UML, Ecore) and annotating the diagrams with declarative constraints (e.g. OCL) to formalize the invariants of the class diagrams. Such meta-models usually describe the category of acceptable systems or system configurations. Once the meta-model is obtained an instance of the meta-model can be created (which would correspond to a particular system or system configuration). Two questions naturally arise in this modeling process. Firstly, a validation problem: does the meta-model adequately capture all informal requirements without error, ambiguity or redundancy? Secondly, a verification problem: are instances correct with respect to the meta-model and its constraints? The following sections give a quick overview of the state of the art of existing validation and verification techniques, and finally introduce the research objectives and current work at Onera.

Validation

At the meta-level, generic properties can be investigated, of which the following two are the most important:

- Constraints consistency: the absence of logical contradiction between constraints that would entail an empty set of instances of the meta-model;
- Constraint non-redundancy: there should exist instances which show that each constraint can be satisfied/falsified independently of the others, proving that each constraint adds its own independent semantic contribution to the meta-model.

Tool support is available for such validation tasks: UMLtoCSP [20], UML2Alloy [19], KodKod [18], etc. which all employ constraint satisfaction techniques to generate witnesses of the above properties. Yet, the integration of these tools in major IDEs is sub-par and tools are not easy to use (incompatible data formats, etc).

Verification

At the instance level, we can make sure an instance is structurally faithful to class diagram constraints (valid types and cardinalities for references). MDE technology allows the creation of instance editors from a DSL specification and creating instances using these editors prevents a lot of basic structural errors; furthermore, any remaining error can be detected using static checkers.

Secondly, we can verify that an instance satisfies all constraints (OCL) of the meta-model. Tools for OCL verification exist (Dresden, Topcased, etc.) and allow the discovery of violations. The performance of these tools is often no better than average (interpretation techniques vs. code generation techniques) and in some contexts there are difficulties in scaling up to real world applications.

Research challenges

This recent state of the art report shows that a lot is already available for MDE users. Yet, two questions remain open today in MDE: how to assist the creation of large and correct-by-construction instances (think thousands of objects under complex constraints)? How to create instances which make sense from an engineering point of view?

These two questions have given birth to a research work on automatic instance synthesis from a metal-model with optimization of quantitative criteria. An Onera proposal is to use modern and robust combinatorial optimization techniques (Max-SAT, Pseudo-Boolean optimization, SMT solving or CSP solving) to synthesize instances of a meta-model which:

- Satisfy all hard constraints of the meta-model.
- Optimize user provided quantitative criteria.
- Can be used to extend existing (and possibly flawed) instances to valid instances.
- Help the users to explore the design-space by proposing alternative solutions to a single problem.
- Scale up to industrial applications.

Model transformation for verification and for code generation

Onera is currently working on a generic model transformation framework to import and translate meta-models and instances to a portfolio of constraint satisfaction engines, as shown on figure 5.

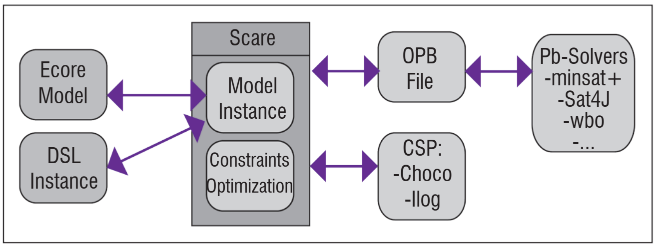

Figure 5 - SCARE framework

For more details about this technology and its possible uses, please consult the following references: [23], [22], [21].

Cooperation of analysis techniques

While formal techniques are slowly appearing in industrial practice, the ecosystem of methods applicable to a system has yet to become more structured. For a specific description level, either at model level with synchronous data-flow languages (Lustre, Simulink, etc.), or at code level (C, Ada, etc.), a variety of formal analysis tools are available. Each of these tools targets a range of properties and, until now, the relationships between them has been only marginally investigated. A direction of research at Onera is focused on an effective combination of techniques to improve both the efficiency and spectrum of formal verification for embedded systems. Gathering different techniques into an integrated framework means the end-user has access a simpler view of what properties can or cannot be analyzed with respect to the available tool set. This research is being developed through two sub-themes with different partnerships.

Theoretical combination framework and application at code level

We are doing this work in cooperation with INPT and Airbus. We propose a theoretical framework that gives us a general way to reason about a block of code annotated with a formal specification, typically a Hoare triple {Precondition} Sequence of Instructions {Postcondition}.

Most of the analysis techniques can be expressed either as forward analyses that over-approximate the reachable states of the code, or as backward analyses that under-approximate the co-reachable states of the code starting from a specific property. The formalization of these mechanisms (see figure 6) allows us to demonstrate how to implement the collaboration of techniques.

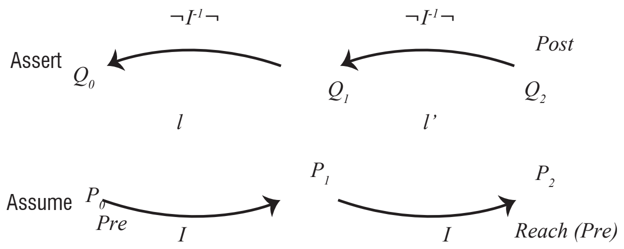

Figure 6 - Forward and backward analyses

Reinforcing the knowledge of an analysis by the intermediate information computed by the other allows a strengthening of the global results.

These ideas have been implemented on C code analysis tools, by combining an abstract interpreter, that over-approximates the collecting semantics (in a forward setting), and a weakest-precondition engine, under-approximating the behavior of the program with respect to the Post property [24].

Combination of k-induction and abstract interpretation at model level

In cooperation with the University of Iowa and Rockwell Collins, this research focuses on the verification of safety properties on Lustre programs. SAT or SMT [25], [26] based verification approaches such as k-induction [27] give good results on programs with a mostly discrete state space (boolean, bounded integers). However, when numerical computations are involved (real/float computations) the formalization of the property to be proved often needs to be strengthened using auxiliary lemmas to make it inductive with respect to the system's transition relation. When attempted manually the discovery of such lemmas is time consuming and hinders the efficiency and scalability of formal verification. Automating lemma discovery hence appears crucial to allowing end-users to apply formal verification on industrial cases.

Our proposal materializes as a parallel analysis framework for Lustre programs in which each analysis can communicate its own intermediate information to the others: discovered invariants, potential invariants, counter-examples to the induction step of a proof, heuristics about relationship between state variables. The exchanged information is used to drive and tune the analysis of the different tools. Abstract interpretation is used to provide bounds on the state variables and to generalize counter-examples, while k-induction is used to validate any proposed invariants and to discharge the principal proof objective. The main components of the engine and their interactions are presented in figure 7.

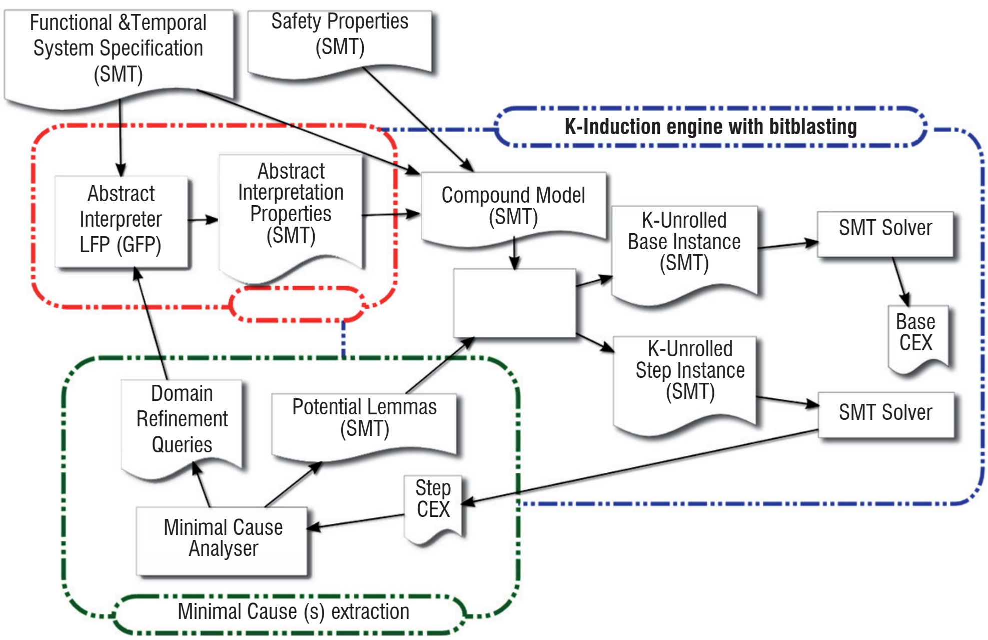

Figure 7 - Cooperation between model checking and abstract interpretation

Test automation using formal methods

Formal verification will not replace all the tests but can help in automating the test process that is still often very manual. Test is composed of three activities: definition of test scenarios, execution of the scenarios and oracle (did the test fail or pass?)

A lot of work has been done on automated test generation from formal specifications [30], [31]. Test scenarios are generated from a formal model of the software requirement in order to test the correctness of the code with respect to the requirements. Automated test generation can also be used to test a design model with respect to requirements. Onera has worked with Airbus on test generation techniques and methods as well as on the definition of relevant structural coverage criteria for SCADE models [28], [29]. Special attention has to be given to the methods used in order to respect the constraints imposed by DO-178B that forbid the use of structural testing.

Onera has also worked on automation of the oracle for the test of SCADE models. SCADE models are tested against functional requirements (written in natural language) on specific simulation environments. Test scenarios are manually defined by testers, then they are executed on the simulator and finally the tester decides if the test results are correct with respect to the expected results specified in the requirements. The oracle can be done online, or offline by looking at the execution traces of the test. We have proposed a formal language for the expression of test objectives derived from the requirements and an analysis technique to automatically verify that the execution traces are correct with respect to the test objective. It has been applied on Airbus critical avionics software [32].

This work on trace analysis can be seen as a run-time verification approach. Run-time verification is a research field that proposes the use of formal methods in a lightweight fashion in order to verify properties on execution of the software (www.runtime-verification.org). Most of the contributions propose techniques to monitor the program while it is executing and detect violations of the properties; but a posteriori approaches also exist that verify the properties on the program traces [33].

Future work

Future work in software formal verification at Onera is going to be focused on three themes.

1) We will continue to investigate the cooperation between different verification techniques, in order to improve efficiency of the verification and augment the spectrum of properties that can be addressed by formal methods.

2) We are going to work on the definition of an optimized verification process across the different development levels. This theme is broad and long term, we will conduct research on the following aspects in particular:

- use of invariants from continuous mathematical models to ease verification of software (cooperation with Georgia Tech);
- combination of static and dynamic analyses: test and formal methods will be used in future software verification processes, but research still needs to be done to find smart ways of combining them.

3) We plan to work on incremental techniques to take into account of software evolutions. In Aeronautics, successive versions of software are verified before being embedded in the aircraft, but also during maintenance. Defining efficient techniques for incremental verification would be very interesting in this context ■

Acronyms

MDE (Model Driven Engineering)
ATV (Automated Transfer Vehicle)
HLR (High Level Requirements)
LLR (Low Level Requirements)
SAT (Satisfiability)
SMT (Satisfiability Modulo Theories)
OPEES (Open Platform for the Engineering of Embedded Systems)
UML (Unified Modeling Language)
OCL (Object Constraint Language)
IDE (Integrated Development Environment)
CSP (Constraint Satisfaction Problems)

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New Challenges for Future Avionic Architectures

Electronic sets operated on aircraft are usually summarized as "avionic architectures" (for "aviation electronic architecture"). Since the 70s, avionic architectures, composed of digital processing modules and communication buses, are supporting more and more avionic applications such as flight control, flight management, etc. Hence, avionic architectures have become a central component of an aircraft. They have to ensure a large variety of important requirements: safety, robustness to equipment failures, determinism, and real-time.

In response to these requirements, aircraft manufacturers have proposed several solutions. This article has a twin objectives: firstly to survey the state of the art of existing avionic architectures, including the IMA (for Integrated Modular Avionic) architecture of the most recent aircraft; and secondly to discuss two challenges for the next generation of avionic architectures: reconfiguration capabilities, and integrating COTS processing equipment such as multi-core processors. We believe that these two challenges will be central to the next generation of IMA architectures (called IMA-2G for IMA 2d generation).

Introduction

Aerospace systems

Avionic systems represent a growing part of aircraft costs: 35 to 40% in civil aircraft, and more than 50% in military aircraft. These systems are responsible for various applications, such as navigation, guidance, stability, fuel management, air/ground communications, passenger entertainment, etc. Their complexity is continuously growing (more and more functions to integrate, the aircraft becomes a real information system). In parallel, communication and information management technologies are evolving and new solutions for avionics are being invented. The implementation of the avionic systems of modern civil (B787, A350) and military (Rafale, Gripen, A400M, etc.) aircraft tends to rely on an IMA (for Integrated Modular Avionic) architecture instead of the more classical federated architecture. In a federated architecture, each system has private avionic resources, whereas in an IMA architecture avionic resources can be shared by several systems. The types of avionic resources that are generally considered are computers with real-time operating systems or local area network with real-time communication protocols.

An important consequence of the emergence of IMA in aerospace architectures is to allow development of x-by-wire[1] distributed applications, composed of a great deal of equipment (sensors, actuators, physical devices, software modules, memory modules, etc.) supported by the IMA platform. That leads to more and more complex systems, which are becoming increasingly difficult to validate.

Aerospace systems requirements

Aerospace systems are often characterized by two properties. Firstly, they are an information processing subsystem of their embedding systems, i.e., the aircraft. Second, they are reactive, i.e., they interact with their physical environment (e.g., the crew, the physical devices, etc.) at a speed imposed by the environment. Consequently, they have to meet a wide variety of constraints imposed by the embedding system and by the environment.

[1] x-by-wire is a generic term used to describe control systems that depend on a real-time communication network to connect different electronic components. Historically, these control systems relied on mechanical or hydraulic linkages, and the goal of x-by-wire is to replace nearly every automotive hydraulic/mechanical system with ultra dependable electronic systems. The "x" in "x-by-wire" denotes any safety-related application, such as steering, braking, flight control.

•*Safety constraints:* by nature avionic systems may cause severe damage if they malfunction. This possibility is dramatically increasing with the emergence of x-by-wire technologies, where critical applications (guidance and stability for instance) are totally managed by software modules. It is therefore of great importance to guarantee that such a system works correctly in all situations. For instance, let's consider a landing gear control system. The system is in charge of maneuvering landing gears and associated doors by controlling a set of physical devices, such as hydraulic jacks. Obviously, this system has to satisfy a list of requirements, such as "if the landing gear command button has been down for a given amount of time t, then the gears will be down in less than t time units". These properties characterize a real-time behavior of the control software together with the communication network between software modules and equipments. Due to the critical nature of the system it is necessary to guarantee that, whatever the behavior of the rest of the system (i.e., other applications), the right orders are sent at the right time to the right actuators (hydraulic jacks, gears, doors, etc.).

•*Dependability constraints:* by nature, embedded equipment may fail (with a given probability). Obviously, catastrophic failures are not acceptable at run time above a given probability level. It is therefore necessary to ensure that the system continues to work well (possibly in a degraded mode) even in the event of equipment failure.

•*Real-time constraints* are of great importance when dealing with x-by-wire dynamic systems. The total time delay is important for stability and performance of closed loop control of the flight control system, the automatic pilot system, the flight management system, the braking system, etc. The time lag between data input and the corresponding output (orders to actuators for instance) are due to (a) computing, (b) communication latency through the "wires" (i.e., the buses, the communication switches...), and (c) storage time. Typically, the inputs are pre-processed before being used in the main computational cycle, and the output will be post-processed after being computed. The pre- and post-processing may involve unit conversion, reasonableness checks, comparison with input from other computers (voting, etc.), and integrity checks on the communication links. In the IMA context, this pre- and post-processing are supported by shared computing resources. Similarly, the main computational cycle may involve several software modules running concurrently on IMA-shared resources and managed by real-time scheduling policies. Due to resources sharing, the time required for these activities may vary but could increase the effective lag between input and output orders above the value corresponding to the specified iteration rate. That could impact the performance of the closed loop control system, and consequently the stability of the aircraft. Guaranteeing and verifying real-time constraints are major tasks when designing and validating aerospace systems.

Safety, dependability and real-time constraints have a direct impact on architecture design at aircraft and system level, and on the validation/certification process. Hence, aircraft manufacturers have to show compliance with international regulations using means that have been accepted by the certification authorities. This includes showing that safety requirements are enforced, establishing the predictability of communication and computing real-time performances and developing software and hardware according to strict development guidelines. This context makes designing and verifying aerospace systems, and particularly avionic architecture, a substantially different and more difficult task than for classical systems and software.

In response to this difficulty, aerospace researchers and engineers have developed two successive families of avionic architectures: federated architectures and IMA architectures.

Brief history: from federated architectures to IMA

From federated architectures…

The first avionic devices to be embedded in aircraft were radios for communication and navigation in the 1940s. Since this period, analog and digital electronic controllers began to replace mechanical aircraft functions and equipment. One of the most popular examples of digital embedded systems is the flight control system (FCS), automatically controlling the trajectory of the aircraft according to the pilot's navigation orders. Until the 1990s the global architecture of the avionic system (including the FCS) was designed in accordance with the "federated architecture" principle: "one function = one computer". Figure 1 depicts an example of a federated architecture: the architecture of the A340 FCS. This system is composed of several software functions (FCPC, FCSC, etc.). Each function runs on a dedicated resource connected to its dedicated sensors and actuators. In other words, each function owns its dedicated equipment, including computing resources, sensors and actuators. Consequently, each function + resources set could be considered as a standalone subsystem. The main advantage of this so-called federated architecture is that it has quite limited resource sharing, and the dependencies between subsystems were well understood.

Up to the end of the 1990s, most of the civil aircraft, including the Airbus family A320, A330 and A340, were based on the federated architecture principle. However, since the 1990s, the airlines want more and smarter functionality, such as precise flight management capabilities, on board maintenance systems, larger entertainment systems for passengers, etc. The concept "one function = one dedicated subsystem" could no longer be maintained. The concept met its natural limit when the weight and volume of the dedicated subsystems hit the envelope restrictions of the aircraft. Another drawback became obvious: the huge number of different resources significantly increased the maintenance costs for airlines in terms of worldwide computer spares provisioning and handling. So a new approach was needed.

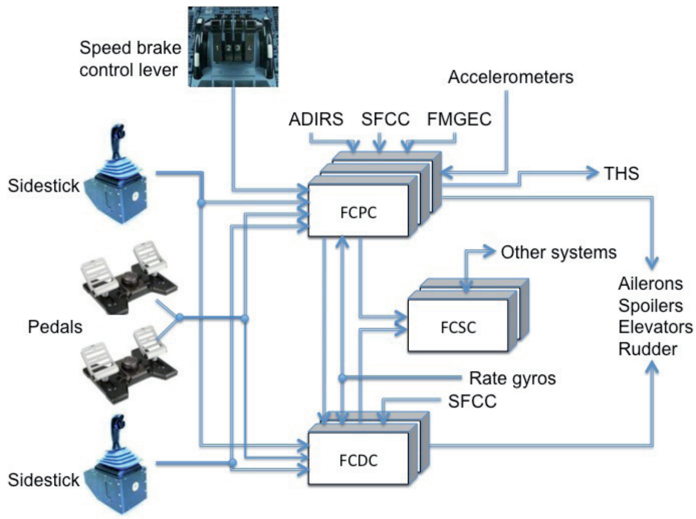


Figure 1. Example of a federated architecture: the A340 Flight Control System architecture

… to IMA-1G architectures

This new approach, called IMA (Integrated Modular Avionics), is based on two complementary principles. The first principle is to integrate multiple software functions with possibly different criticality levels on single avionic computing resources in order to keep the weight, volume and cost of the avionic architecture within reasonable limits. However, due to resource sharing, this first idea leads to side-effects and non-functional dependencies between avionic applications. Troubleshooting and modifications become very difficult. Moreover, proving that the system behaves safely requires knowledge of the whole system. It cannot be done in an incremental way function by function, as in previous federated architectures, and design and the certification process become a nightmare.

So a second principle is needed to simplify the design process and receive certification: strict and robust partitioning, i.e. a set of principles implemented by hardware and software means (such as middleware) which prevent interference between functions, exactly as if each function runs on its own virtual resources with guaranteed performances whatever the behavior of other functions.

IMA-1G (for IMA first generation, developed and certified for A380 and B787) is based on these two principles.

IMA-1G: description and main principles

Resource sharing and robust partitioning are the central ideas of the IMA concept. They are based on two standards: ARINC 653 [1] which defines partitioning principles in processing modules, and ARINC 664 [2] which defines partitioning principles for communications between functions.

Processing module partitioning

ARINC 653 specifies the management of avionic applications on common processing modules. As has already been explained, an avionic application is composed of several software functions running on different processing modules. According to ARINC 653 principles, functions from different applications resident in a processing module are partitioned with respect to space (resources partitioning) and time (temporal partitioning).

• *Resources partitioning*

Each partition is allocated a set of spatial resources (memory, non-volatile memory, I/O resources, etc.) in a static manner, that is to say that the module integrator has the task of assigning maximum allowed resources to each partition while respecting space segregation between them. Low-level mechanisms (at operating system level) provide protection for partition data against any modification from the other partitions. They monitor function activity with reference to allowed resources which are statically allocated through configuration tables.

• *Temporal partitioning*

The scheduling of functions on each module is defined off-line by a periodic sequence of slots statically organized in a time-frame named the MAjor time Frame (MAF). Each function is allocated a time slot for execution. At the end of this time slot the partition is suspended and execution is given to another function (from another application). Thus, each function periodically executes at fixed times.

Functions become in this manner totally independent, where faulty ones can be isolated without affecting much of the system integrity.

Communication resources partitioning

Arinc 664 describes the management of communication resources (i.e., the communication network). Communication flows are statically segregated into Virtual Links (VL). Each VL is dedicated to a single function and implements a traffic shaper. It is characterized by a Bandwidth Allocation Gap (BAG), i.e., the minimal time interval separating two successive messages on the VL. This principle has been implemented in the Avionics Full Duplex Ethernet (AFDX) architecture. AFDX constitutes one of the major technological breakthroughs in the avionics of the A380. In effect, and for the first time for such an aircraft category, the avionic system is based on a redundant and reliable Ethernet network. Key criteria for the choice of AFDX technology were avionic-specific constraints (security, temporal problems), the arrival of Ethernet switching and the size of the computer market. The final choice is therefore the switched Ethernet (full-duplex mode). The AFDX standard defines the electrical and protocol specifications for the exchange of data between Avionics Subsystems. One thousand times faster than its predecessor in the old federated architectures: the ARINC 429 bus.

A typical IMA platform is described in figure 2. Its hardware architecture consists of a set of computing processing modules (called CPM) that are connected to ARINC664 communication switches. CPM are grouped into clusters so that all the CPM in a cluster are connected to the same communication switch. Avionics applications (labeled A1 to A3 on CPM1, B1 to B3 on CPM2, etc.) are hosted in the partitions running on the computing modules. Data flows exchanged by applications hosted on different computing modules are transmitted through communication switch paths that connect the two computing modules.

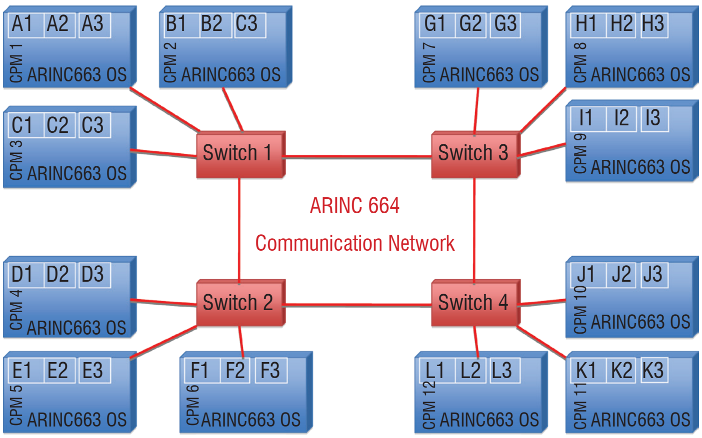


Figure 2. Typical IMA-1G architecture

The two standards ARINC 653 and ARINC 664 globally define the IMA concept that has been implemented in the Airbus A380 and the Boeing B787 for instance.

IMA-1G: benefits and impacts

Several benefits and impacts of IMA are discussed in [12]. The benefits are mainly weight and power consumption reduction. However, new difficulties arise: understanding and side-effects and dependencies between applications due to resource sharing.

Weight and power consumption reduction

Since IMA makes use of shared computing resources, the circuitry that once was contained within each federated resource (dedicated to a given function) is now contained within a common IMA platform. For instance, computing processors that were duplicated in the federated case for fault-tolerance are replaced by a common set of IMA processors (and the associated infrastructure such as power, cooling, and redundancy mechanisms). Similarly, dedicated communication links are replaced with common communication channels (and the associated wiring). And finally, dedicated I/O interfaces are replaced by common I/O interfaces (and the associated wiring).

Globally, IMA results in a reduction in the required physical resources. Reduced physical resources translate to global weight and power savings for the aircraft. For instance, the number of processing units in the A380 is half that of previous generations. Reductions in airline operating costs are expected to be significant, with the decrease in the number of computers and cables (for power supply or communication) contributing to a reduction of aircraft weight leading to better fuel consumption efficiency. In the same way, fewer types of equipment will mean the airline has to buy and store fewer types of spare parts, which should lead to savings in maintenance costs.

Side-effects and dependencies between applications

The IMA architecture has a considerable impact on system development, as it is no longer possible to develop a system or a subsystem without considering its dependencies due to resource sharing with other systems. Of course, in federated avionic systems, functional dependencies between applications must be identified and taken into account. For instance, several aircraft applications, such as flight controls, depend on the navigation system or on the radioaltimeter system for altitude data. Hence, the impact of the loss of navigation or radioaltimeter data is taken into account when developing the flight control system. But resource sharing adds new indirect dependencies, similar to side-effects, between systems or subsystems. With regard to system safety, shared resources might cause common-cause failures. In the same way, resource sharing might cause unpredictable (or at least difficult to predict) overloads, implying delays and possibly a missed deadline or loss of information at run time. Let's consider the example of navigation data, produced by the navigation function for the flight control system. Assume that navigation data is allocated to a communication bus that is also in charge of transmitting diagnostic and maintenance information. It could then happen that, if a failure occurs somewhere in the aircraft (even on a non-critical equipment), the alarm and maintenance information overloads the communication network, leading to delays or to the navigation data not being transmitted. Such a scenario might lead to a catastrophic situation, although the initial single failure is of minor importance.

More generally, multiplexing all avionics communication flows on standard COTS communication resources would not have maintained the guarantees (in terms of guaranteed bandwidth, segregation, determinism) provided by dedicated avionic buses (like the ARINC 429 standard used in the federated architectures). For instance, traffic confluence inside Ethernet switches lead to variable latency. Hence, without any further assumption on a limitation of the communication flows, the occupation rate of each output port of each communication resource in the network is not predictable. Therefore, end-to-end latencies through the network are not predictable.

The second important benefit of the AFDX architecture is that, if functions are statically allocated in modules and if all functions respect their communication contract (i.e. the bandwidth allocation gap associated with each virtual link), then it is possible to mathematically prove that

- *no message is lost during the communication (i.e. no queue will overflow)*,
- the end-to-end delay of any message is bounded, and it is possible to evaluate an over-approximation of this bound.

These assertions do not guarantee absolute behavior determinism, but only a weaker form of determinism, which is sufficient to bring the guaranteed service required by essential avionics systems. Moreover, a "last but not least" benefit is that the certification process of the IMA communication network is (partly) based on this mathematical proof. This proof is based on the network calculus theory [10] (see also Chap. 15 of [18]). Network calculus is a recent analytic technique dedicated to switched communication networks. Input and output flows of the network are defined by positive increasing functions. Each node in the network (the switches) is then defined by its service curve [8]. Informally, the service curve determines the quantity of information, which may have been served until a given duration. Such a theory allows the formal determination of upper bounds, such as queue capacity required in each switch, and global maximum response time needed for each flow to cross the network. Network calculus has been used for certification of the A380 avionic network, and is now integrated in the Airbus network development process.

Next steps: two new challenges for IMA architectures

Towards reconfiguration capabilities

As explained above, IMA architectures have been defined to design avionics platforms that share communication and computation resources according to the two standards ARINC 653 and ARINC 664; these two standards impose static and fixed allocations. However, it could be interesting, in the event of a hardware failure for example, to be able to reconfigure the system, which means reallocating functions to safe modules. To meet this objective, the next generation of IMA platforms are to include reconfiguration capabilities in order to limit the effect of hardware failures on aircraft operational reliability. Such a reconfiguration capability is one of the next great challenges for avionic architectures.

Onera, in collaboration with Thales and Airbus, has explored the reconfiguration issue for IMA architectures in the European SCARLETT project [2]. The solution proposed for introducing reconfiguration capabilities in the next generations of IMA architectures is developed in section 3.

Towards high performance IMA architectures

The last decade has seen the emergence of multicore and manycore architectures, i.e. chips integrating several cores. These architectures are replacing the "old" monocore processors in all commercial domains, including avionics. The integration of monocore processing modules in IMA architectures is becoming more and more expensive because of the ongoing scarcity of these components.

[2] http://www.scarlettproject.eu/, point of contact: didier.hainaut@fr.thalesgroup.com

As a consequence, multi and manycore processors will be unavoidable in the next IMA-2G architecture.

They also offer promising opportunities for airframers due to their high level of computing power. The use of more flexible and lighter structures, for instance, means embedding far more complex flight control systems needing short response times and huge computations. It is expected that suitably controlled multi or manycore systems will provide the appropriate increase in computation power needed by these complex applications, paving the way towards greener aircraft by reducing aircraft structure weights.

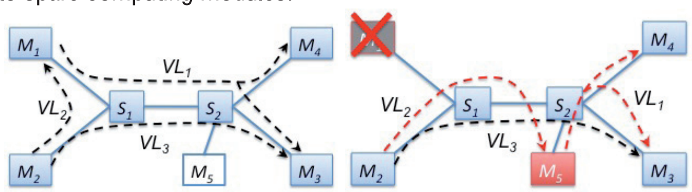
However, embedding multi or manycore architectures is a real challenge because they make it hard to ensure time predictability due to intensive resource sharing and because they do not satisfy the same fault model as monoprocessors.

Onera, in collaboration with Thales and Airbus, has explored this challenge. A first solution has been proposed for embedding predictable multicore architectures in avionic systems. This first step towards high performance IMA architectures is discussed in § "Second challenge".

First challenge: towards a reconfigurable architecture

Objectives and main ideas

Reconfigurable IMA should be able to change the configuration of the platform by moving applications hosted on a faulty computing module to spare computing modules.



(a) Initial configuration (b) Configuration after losing module M1
Figure 3. Reconfiguration example

Let's look at the notion of reconfigurable IMA with a simple example: the platform is composed of five modules ($M_1,\ldots, M_5$) and two communication switches ($S1$, $S2$). The initial configuration is drawn in figure 3(a): module M_5 is a spare initially shut down and free of application (in white in the picture). If some failure occurs on module M1 then the applications initially hosted on this module can be reconfigured on the spare M_5, and all communications from and to M_1 ($VL1$, $VL2$) have to be rerouted according to this new allocation. The configuration obtained is shown in figure 3(b) (reallocations are shown in red).

The main goals to be achieved by the reconfigurable IMA platform are to:

- Improve the operational reliability of the aircraft while preserving current levels of safety;
- Avoid unscheduled maintenance and associated costs;
- Limit the impact of reconfiguration on certification practices and effort.

Aircraft systems have to enforce stringent safety requirements that address the effects of failures on the life of passengers. To satisfy these requirements a minimum level of redundancy is associated with an application on the basis of the severity of the effects of its loss. For instance, three occurrences of an application managing cabin air pressure would be required because loss of cabin pressurization is catastrophic whereas no occurrence of an application managing in-flight entertainment is required, as it is considered as a comfort application the loss of which has no safety effects.

Operational reliability addresses the effect of failures on economical aspects of flight operations. One source of improvement is to decrease the number of flight delays or cancellations caused by faulty computing modules. Before each flight, the health status of all equipments is assessed in order to check whether for all applications the correct level of redundancy is available. If this is not the case the aircraft cannot be used (NOGO). It should be possible to restore the minimum level of redundancy by moving the applications running on the faulty module to a non-faulty one. This should also help to defer maintenance operations until the aircraft has reached an appropriate location.

Reconfiguration constraints and principles: a first proposal

According to the IMA standards, several functions are available in order to manage the platform, they include a:

- *Data-Loading* function that stores all the application software and loads the application software in accordance with the allocation of applications onto the computing modules;
- *Monitoring and Fault Detection* function that constantly receives information about the health of the hardware components and is able to detect that a component is faulty;
- *Power Supply Management* function that is able to switch on and off the power supply of the various hardware components of the platform.

For reconfigurability purposes, a new function, called the *Reconfiguration Supervisor* (supervisor for short), needs to be embedded in the aircraft. The role of the supervisor consists in determining when a reconfiguration can occur and in performing a "correct by construction" modification of configurations in order to reach a better and safe state. The supervisor behavior is described by the following:

1 - Triggering a reconfiguration

When a computing module fails, a reconfiguration can be launched if this failure has an operational reliability impact, meaning that the aircraft becomes NOGO. The Monitoring and Fault detection function detects a NOGO module failure and sends this event to the supervisor. First, the supervisor applies usual maintenance procedure to check that the failure cannot be repaired by a simple reset of the module. For this it interacts with the Power Supply Management and the Monitoring and Fault detection to check if the reset has repaired the module. If the reset works then the module restarts the hosted avionics applications and the failure is corrected; otherwise the supervisor performs the next steps.

2 - Selection of a correct configuration

When the failure is confirmed the supervisor must determine the current state of the platform in order to select the next configuration. The sorting takes into account the side-effect on aircraft and the duration of the reconfiguration execution. The selection process is the following:

• *Set of configurations*

We note $Application$ the set of applications hosted by the platform, $Cluster$ the set of clusters of the platform, $Basic\_Module$ (resp. $Spare\_Module$) the set of modules (resp. spare modules) in a cluster and $Basic\_Partition$ (resp. $Spare\_Partition$) the set of partitions (resp. spare partition) running on a module. Let us denote $bm=|Basic\_Module|$, $sm=|Spare\_Module|$, $c=|\mathrm{Cluster}|$, $f=|\mathrm{Application}|$, $bp=|Basic\_Partition|$ and $sp=|Spare\_Partition|$.

Definition 1 (Configuration)
A configuration is an allocation of avionics applications on computing elements and it is represented by a function

$$Conf: Application \rightarrow Computing\_Element$$

where the set $Computing\_Element$ *is defined by* $Cluster \times (Basic\_Module \cup Spare\_Module) \times (Basic\_Partition \cup Spare\_Partition)$.

For module level reconfiguration, the identifier of the partition for an application remains unchanged wherever the application is allocated. Therefore, we can optimize the set to be $Computing\_Element=Basic\_Module \cup Spare\_Module$. In figure 1, avionics application $A1$ is allocated in its initial partition on the first module of the first cluster. Thus $Conf(A1)=(1,1,1)$. For module level reconfiguration, there are exactly $(c(bm+sm))f$ configurations. This corresponds to the number of integer functions $[1,f]\rightarrow[1,c(bm+sm)]$. For partition level reconfiguration, there are exactly

$$A^{f}_{(c(bm+sm)(bp+sp)} = \frac{(c(bm+sm)(bp+sp))!}{(c(bm+sm)(bp+sp)-f)!}$$

configurations. This corresponds to the number of injective integer functions $[1,f]\rightarrow[1,c\times(bm+sm)\times(bp+sp)]$. All these configurations are known at design time. Note that we only consider nominal configurations and not degraded ones where an avionics application may not be allocated because there are not enough fail-free computing elements. The sequences of possible reconfigurations starting from an initial configuration can then be represented by a directed acyclic graph.

• *Reconfiguration policy*

The reconfiguration policy defines generic rules to be followed. It is chosen off-line and impacts the on-line selection process of the next configuration. For instance, we can decide that there is no priority among avionics applications and then, once a spare has been occupied, no other application can be hosted on this spare. Or we could associate a priority level with the applications and then a reconfigured application can be removed to leave the spare to a failed application with higher priority level. Another rule can give an order on the spares. The policy would then consist in reallocating on the first spare if it is available, otherwise on the second if this one is available and so on.

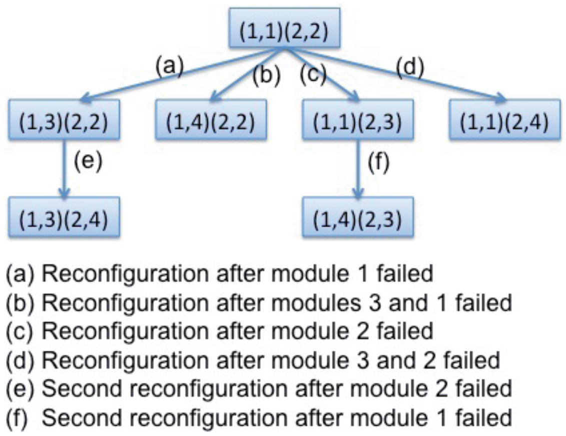
Let us consider the architecture $f=2,\ c=1,\ bm=2,\ sm=2$ where a module can host at most one application. For a module level reconfiguration we obtain several directed acyclic graphs of reconfigurations depending of the policy. For any of these graphs a node corresponds to a configuration, which is a list of pairs (number of application, number of hosting module). Below are shown the graphs associated with two policies that both order spare modules:

On the first graph (figure 4(a)), spares are not reconfigured, meaning that if a spare fails then hosted applications are lost. While on the second graph (figure 4(b)) they can be reallocated. For instance, transition (g) corresponds to a reconfiguration consecutive to the failure of the spare module 3. Reconfiguration graphs are different. Transitions (g) and (h) are missing on the left side graph because, according to this policy, when application 1 is running on spare 3 and this spare fails it is not possible to move 1 to spare 4.

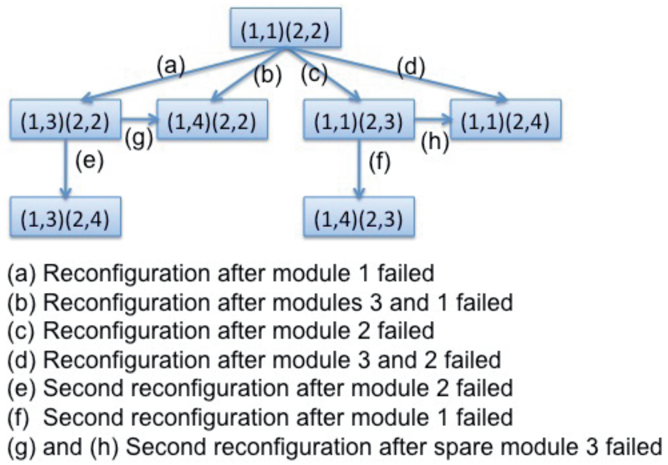
• *Resource and real-Time constraints*

A configuration is safe if it satisfies some constraints. For instance, an application can be hosted on a module only if it provides adequate resources for the application such as processing power or memory. There are other kinds of constraints, such as segregation, that are described in [14].

A transition is safe if the intermediate steps are safe (they do not impact the integrity of the aircraft) and the duration of the transition is bounded by an appropriate value. The transition from one configuration to another is done by applying several basic procedures. All such elementary procedures are stored in some repository associated with a WCET (worst case execution time). For instance, data-loading a complete module is an elementary step and always takes less than a bounded amount of time, which is computed off-line. Globally, major reconfigurations done on the ground during two consecutive flights must take less than 15 minutes in



(a) First policy: without spare reallocation



(b) Second policy: with spare reallocation

Figure 4. Examples of reconfiguration graphs

order to limit the flight delay. Minor reconfigurations done in-flight must complete more quickly according to the real-time requirements of the functions to reconfigure (generally less than several milliseconds).

• *Continuity of service*

When a module fails, the other avionics applications should not be impacted by a reconfiguration. In the case of partition level reconfiguration, the interactions between the supervisor and modules involved in the current reconfiguration must be transparent for the other partitions. For instance, data-loading and initialization must be realized during the partition time. In the case of distant reconfiguration, the routing of the impacted switches must be modified while ensuring the continuity of the remaining traffic.

3 - Reconfiguration execution

If a correct transition, with respect to the avionics constraints and the reconfiguration policy, has been found, the reconfiguration is performed. Basically, a reconfiguration is broken down into elementary steps: power up a spare module or a spare partition on a running module, test that the spare is fail-free and load the time application sequencing (at module level), data-load the code and initialize the partitions on the spare (during predetermined time slots for partition level), then verification by Monitoring and Fault detection that the spares are working correctly. A notification and report are sent to the maintenance terminals.

The sequence execution should be transactional and secure, i.e. the sequence should entirely succeed or totally fail. For this purpose, each step is acknowledged (succeeded, failed, not performed). Any step can be aborted without a side-effect on aircraft safety, performance and security. For instance, an access to an already allocated memory must be refused by Monitoring and Fault detection.

Discussion: mid-term and long-term perspectives

About the certification issue

Certification practices require safety assessments and showing real-time predictability for all configurations of a system. Two approaches can be considered. The first one consists in validating all the possible configurations. Currently, in an IMA-1G platform there is a unique configuration, which is completely certified. Because of the large number of reachable configurations (for c=4, bm=5, sm=1 there are 1296 configurations for local reconfiguration and 146001 for distant reconfigurations) the certification of an IMA-2G process must evolve in order to certify a family of configurations. Model based safety assessment, as described in [14], should be able to cope with the large number of reconfigurations. For real-time performance predictability it should be possible to consider that a local module reconfiguration in a cluster has no impact on performance.

A second approach could consist in certification of the tools used and the process followed for the generation of the configurations. This second approach is independent with the number of possible configurations, provided that the generation process is mainly automatic. This second method has not been explored by the recent work. However, it could be a promising alternative for the certification issue.

First lessons and next issues

The reconfiguration objectives explored by this preliminary work have the aim of enhancing the operational reliability of the aircraft. This is a different goal from the reconfigurable avionic systems proposed in the literature [15,11,16,9,3] where reconfiguration is one means to achieving fault tolerance. Similarly, the classic FDIR (Failure Detection Isolation and Recovery) procedure used in most space systems uses dynamic reconfiguration during the recovery phase. In those cases the system is statically configured with a set of may-be-redundant (but specialized) equipment which may be powered off/on when failure occurs. In the SCARLETT project we aim at configuring generic resources, i.e. IMA modules, with uploadable software functions.

However, even if our primary objectives are different, the methodology, the software and/or hardware architecture design [15,9,11] are helping us toward our goals:

• The steps of reconfiguration process are usually the same (error diagnostic, select new configuration, apply configuration, etc.)

• The widespread idea of precomputed and identified configuration as a means to certifying configuration seems appealing,

• The need for timing constraint considerations in the reconfiguration process for real-time application. Furthermore, the reconfiguration principles presented in the ASAAC standard (see [3]) for military aircraft IMA will be of particular interest if we want to explore the distributed implementation of the reconfiguration supervisor.

Mid-term perspectives would be the implementation of an on-the-ground module and partition level reconfiguration. We also plan to detail the analysis of the proposed solution in terms of operational reliability, safety and certification. A longer-term perspective is to study other scenarios including in flight reconfiguration and reconfiguration for safety.

Second challenge: integrating high performance processors for time critical functions

Multicore architectures have reached the embedded systems market quite recently. They feature high integration and a good performance-per-watt ratio thanks to resource sharing between cores. Standard multicore include 2 to 8 cores on the chip. Cores usually have one or two levels of private instruction and data caches and share an additional level, as well as a common bus to the main memory. Such architectures often implement hardware cache coherency schemes that allow running parallel applications designed under the very convenient shared memory programming model.

Unfortunately, resource sharing makes the timing analysis of critical software very complex if not infeasible. This is due to the difficulty of taking all the possible inter-task conflicts into account, in particular when the cache coherency controller generates implicit communications. For these reasons we believe that multicore processors will be difficult to use for the design of safety critical systems.

On the other hand, many-core architectures limit resource sharing and favor explicit communications between cores. Many-core chips include numerous cores (more than 16) with distributed memories (so the conflicts are limited) and a complex communication network based on a network-on-a-chip (NoC) technology. They do not feature hardware cache coherency and the inter-core communications must be explicit, either to implement software-controlled cache coherency or the message-passing model.

We are convinced that such features are more suitable for safety critical systems in the sense that inter-core communications are software-managed and thus more predictable. However, conflicts on the network still may occur due to implicit accesses of the main memory on cache misses and must be considered when performing timing analysis.

The challenges

Many-core platforms involve several non predictable mechanisms for managing the resource sharing which make it hard to ensure time predictability. Most of the works in the literature on many-core architectures are concerned with high performance: the idea is to extend and adapt current operating systems to the new architectural organization [6,17,13]. The main concern of an embedded system designer is somehow different: he/she wants to determine the worst-case behaviors in order to verify that the hard real-time requirements are always met, rather than to study the average performance. Three challenges arise.

First challenge: processing timing analysis

The first requirement for implementing a safety critical system on a platform is the ability to determine the worst-case execution time (WCET) for any task. The possible interactions and resource contentions due to the task concurrency must be taken into account. The widespread method based on measuring the execution time of a function on the target has been demonstrated to be generally speaking unsafe. The preferred approach is static timing analysis based on modeling techniques, which determines a safe upper bound for the WCET [4]. However, this approach is not yet suitable for many-core architectures. Improving this approach for many-core platforms and for time critical applications is the first next challenge to solve for integrating high performance processors in avionic architectures.

Second challenge: communication timing analysis

Knowledge of the timing behaviors of the accesses on the internal network is fundamental. The user must determine at what time an access is made, where and when a message crosses the network or memory components. The algorithms to compute communication time bounds are, of course, dependent of the communication technology. And this technology has dramatically changed moving from monoprocessor to many-core systems. As the number of components on a chip was low, the medium was a simple bus. In that case, only one device can drive the medium at a time, with a bus arbiter and an arbitration policy (such as round-robin, static priority or TDMA). But with the many-core generation the communication architecture has been enriched to allow a routing network, leading to the so-called networks-on-chip (NoC). In that case, there are links and switches, using either packet-oriented switching (store and forward), circuit-oriented switching (cut-through), or some intermediate policy (like the wormhole).

Most of the research on worst-case communication time have been made for external networks and bus [7]. These results are expected to be reusable for the many-core internal network.

Third challenge: memory access timing analysis

The last components that are difficult to predict are the memory controller and the memory. A RAM is a 3-dimensional storage component organized in banks, rows (or memory pages) and columns. An access (a read or a write) refers to a reference (num bank, num row, num column). The memory controller sends the command to the memory, it can ask for an activation which consists in storing a row in a buffer, a read or a write on an opened row, or a precharge which consists in saving and closing a row. All these commands require some timings. The memory response for a read also takes some time. The memory controller FIFO can sometimes reorder the references. To be able to predict worst case Memory access time for IMA many-core modules with several avionic applications becomes a real challenge.

A first solution for improving many-core predictability in avionic architectures: time oriented approaches

Any critical systems designer has to cope with these problems and has mainly two approaches to safely embed a many-core architecture. The first involves designing specific predictable processor architectures. In this way it is possible to greatly improve worst-case analyses. The cost of such specific hardware developments may often prevent their use and may force the designer to rely on a COTS. The second approach is therefore to apply an execution model: the idea is to define some rules that constrain and reduce the number of non predictable behaviors. If the rules are well chosen, the system may be analyzed without too much pessimism. The basis of this is applying time oriented mechanisms by constraining the behaviors within timing slots.

Time oriented approaches help the arbitration to shared resources. These solutions are well suited within the context of critical embedded systems since they make the formal verification easier and simplify the programming. The idea is to off-line allocate timing slots where the behaviors are constrained and thus analyzable.

Onera and Airbus have proposed a time oriented execution model on multicore to force the COTS to be deterministic [5]. The idea is to distinguish on each core the moments of functional computation and the moments of read/write from/to the memory. These two types of accomplishments occur separately in distinct pre-defined slices. Each core is assumed to have a local clock physically derived from a common hardware clock. Consequently, the concept can apply on a COTS. The separation of behaviors leads to several interesting real-time properties: the functional behavior is fully deterministic; the static WCET evaluation of an execution slice is reduced to a static WCET evaluation of a non preemptive sequential code on a monoprocessor, which is a well-known problem; and the worst case interference on the communication network between the cores and the memory is predictable.

Discussion, mid-term and long-term perspectives

These last results obtained by Onera and Airbus seem to be promising. They allow the embedding of many-core processors for time critical avionic computers to be considered. However, a new question arises: how to embed such a component into an IMA architecture. The challenge is two-fold. Firstly guaranteeing that different avionic functions implanted on the same module do not interfere, which could be done by an extension of the previous time oriented execution model. The second question is more promising and concerns the assessment of the worst-case behavior of each function. The question is: it is possible to determine this worst-case behavior for a given function without knowing the internal behavior of the other functions running on the same module. This modularity issue is central in the IMA development process. This will be the one of main issues for the next IMA-2G architecture ■

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Acronyms

AFDX (Avionics Full Duplex Ethernet)
BAG (Bandwidth Allocation Gap)
COTS (Commercial Off-The-Shelf)
FCPC (Flight Control Primary Computer)
FCS (Flight Control System)
FCSC (Flight Control Secondary Computer)
FDIR (Failure Detection Isolation and Recovery)
IMA (Integrated Modular Avionics)
I/O (Input / Output)
MAF (Major Frame)
NoC (Network on Chip)
VL (Virtual Link)
WCET (Worst Case Execution Time)

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Multidisciplinary Aerospace System Design: Principles, Issues and Onera Experience

With the increasing complexity of aerospace systems, it has become more and more necessary to adopt a global, integrated approach from the very early steps and throughout the design process. Tightly coupling aerodynamics, propulsion, structure, trajectory, guidance and navigation, while also taking into account environmental and societal constraints, as well as manufacturability, reliability and maintainability, is a huge challenge. The field of Multidisciplinary Design Optimization (MDO) provides some answers on how to integrate increasing knowledge into the design process, while reducing the design cycles. It consists in a core of key methodologies, such as multi-disciplinary problem formulation and decomposition, optimization under uncertainties and surrogate based high-fidelity tool integration, which are validated and enriched through confrontation with various kinds of design studies. The aim of this paper is, on the one hand, to give a clear view of the challenges at stake and the key difficulties that must be overcome and, on the other hand, to focus on some significant studies and achievements at Onera over the past decade, either on tools and methods, or on dedicated applications, illustrating the progress made and the challenges to come.

MDO approach in an aerospace context and methodological challenges

Context

In a context of technological breakthrough and increasing complexity, with technologies interacting together in a way that prevents each of them from being handled separately, there is a wide field of development for multidisciplinary design methods and tools. Additionally, there are increasing constraints that must be taken into account when defining new aerospace vehicles, from operational requirements and regulation compliance to public acceptance and environmental performance.

In every scientific domain addressed, such as for example aerodynamics, structural mechanics or aeroacoustics, improvements can only be obtained by accurately handling complex phenomena, which requires, on the one hand, high-fidelity and efficient modeling and, on the other hand, large computational resources. This is mandatory to enable detailed exploration of the design space and significant performance improvements.

In addition to these disciplinary-centered requirements, the tight coupling of several phenomena interacting together makes it a huge challenge to find a global optimum for the entire system, which can be very far from a collection of single-discipline optimizations. The search for this optimal performance stresses the need to adopt an integrated design and optimization approach, allowing sufficient knowledge to be included in the performance analysis. Traditional design processes – where disciplinary knowledge is only handled by the dedicated expert or team – must hence be merged into a global approach, with corresponding methods and tools. This also requires the multi-fidelity problem to be handled, which means keeping the system consistency, using low-fidelity approaches and refining some key performances, by including high fidelity processes adequately coupled to the system analysis.

Multidisciplinary Design Optimization: in brief

Multidisciplinary Design Optimization (MDO), also known as *Multidisciplinary Optimization*, is a relatively recent field of engineering sciences whose objective is to address design problems more efficiently by incorporating various disciplines. The MDO has been used in a great number of domains, such as structure, automotive, electronics or aerospace engineering and allows complex problems, which are difficult to handle with the classical design methods, to be solved. MDO approaches have emerged between 1970 and 1990, with the increase of computer-aided tools and a need to take into account manufacturability, reliability, maintainability and also the worldwide spreading of the main aeronautics companies. Indeed, this increase has made the numerical optimization of complex problems possible and has paved the way for complete system design.

By handling the various disciplines simultaneously, MDO techniques facilitate the search for a global optimal design, which may not be obtained when the disciplines are handled sequentially. Indeed, in most design problems, the various disciplines may lead to antagonistic decisions (*e.g.* structure and aerodynamics in launch vehicle design, as we shall see later). In such cases, MDO techniques are aimed at finding compromises between the different disciplines, in order to achieve a global optimal design.

Handling a series of disciplines at the same time significantly increases the complexity of the problem to solve. One of the branches of the MDO field is dedicated to making new formulations of the optimization problem, aimed at reducing the complexity of the problem and at allowing the more efficient use of traditional optimization methods. Many MDO methods have been developed and can be found in literature [2][3][8][65][70].

Instead of disciplinary codes in a computer, or computer networks, MDO may also address design problems involving engineer teams all over the world. Indeed, due to the globalization of the industries, system design can be distributed among various research centers located in different countries. In this case, the data exchanges between the teams become a crucial point in the design process and MDO provides new tools for the designers, in order to make the design process more efficient.

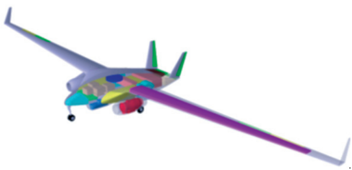
Onera positioning

US universities and government agencies have played a large role in the development of these methodologies, especially with the work on decomposition methods of Dr. Sobieski from NASA Langley, who is also founding chairman of the AIAA technical committee on MDO [26]. In Europe, several initiatives have been conducted by research agencies and universities and now tend to be integrated into a lot of FP7 projects. On both sides of the Atlantic, the work is concentrating on the development of integrated MDO capabilities, such as ANR-OMD, OMD2 or the System@tic CSDL projects in France. Taking into account this need for design methodology improvement, Onera has been making an important internal effort to develop tools and techniques that will help to build efficient design processes and optimization capabilities. The core of this methodological effort is a 4-year internal project called DOOM (Multidisciplinary Optimization Tooled Approach), conducted between 2004 and 2008, and extended by several applicative studies in the field of civil aircraft, Unmanned Air Vehicles (UAV), launch vehicles and missiles. This important development, together with its central position in the French aerospace context, has made it possible to build a strong competency which is still continuously under improvement.

Vehicle design studies: how can complexity be mastered?

A large span of applications

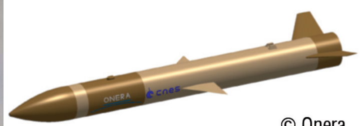
As the French aerospace center for applied research, Onera has an assigned mission ranging from developing disciplinary skills in key fields, such as aerodynamics, propulsion or structure, to overall integration into a coherent system design. For the latter, the challenges are to master the complexity of multi-physics and high technology systems and to generate innovative concepts beyond well-known solutions, with a methodological approach being sufficiently generic to be applied to very different domains. In fact, Onera covers the complete field of aerospace systems, from civil aircraft to orbital vehicles. This paper is focused on air vehicle design. These design studies can be related to civil aircraft (integration of new propulsion technologies and new concepts such as flying wings), UAVs (from flapping wing micro-air-vehicles to large size HALE UAVs), conventional and air-breathing missiles (mid-life evolutions of an existing system, new high speed concepts), launchers and orbital systems (classical ground launched systems and innovative air-launch concepts).



CAPECON UAV design
(European cooperation)

Air-breathing strategic missile ASMP-A
(Onera / MBDA)

EOLE air-launch demonstrator
(CNES/ PERSEUS)



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Micro launcher for DeDalus air launch studies (CNES)

Figure 1 – Examples of vehicle designs in various fields

These design studies also differ by the needs of the customers: they can be either technology-oriented (assessment of the system impact of a new technology for a subsystem manufacturer), driven by industrialization constraints (co-design with industrial actors), require performance sensitivity to changes in the constraints (expertise for MoD or civil authorities) or be aimed at creating fully new vehicle concepts (internal prospective studies).

Typology of studies

To illustrate the differences between these system studies and to better characterize the need for adequate design methodology, they can be classified along 2 axes:

- The level of modeling fidelity that is required by the study (horizontal axis): number of design variables, disciplines involved, fidelity of the models (from analytic to high-fidelity Computational Fluid Dynamics, or Finite Element Methods);
- The "unconventionality" or originality of the design with respect to well-known solutions (vertical axis): new exploration topologies, unusual flight domain (low Reynolds number, high Mach number, *etc.*).

Four families of design studies can be roughly identified:

1. Conceptual design of well-known systems (*e.g.* missile quick sizing loops);
2. Exploration of innovative configurations at a conceptual design level (*e.g.* flying wing, Orbital Transfer Vehicles);
3. Preliminary design of well-known systems (*e.g.* technology integration on a civil aircraft);
4. New types of vehicles with insufficiently known physics (*e.g.* scramjet missiles, flapping wing UAVs).

Moving upwards and towards the right on the diagram, the complexity of the processes involved increases. More design variables, higher fidelity of modeling and greater exploration needs require the definition of more and more integrated processes with advanced MDO techniques. Furthermore, for a same vehicle, MDO can be applied at different levels of the design process and with different degrees of complexity (coupling identification, design problem formulation, uncertainty handling, optimal use of surrogate models, *etc.*).

General MDO approach

In this section, we describe the different steps of a generic MDO approach, in order to handle a design problem.

Design process set up

The first challenge for advanced MDO is to deal with the multidisciplinary aspect of vehicle design. Before talking about design space exploration and optimization, the first obstacle to overcome is the analysis problem, which means the identification of disciplinary couplings and the computation of objectives and constraints as a function of the design variables. However, what is quite obvious in the case of mono-discipline, or even bi-discipline optimization, becomes really challenging when dealing with a process involving at least 4 or 5 disciplines, with multiple solutions.

The aim is to build a design process that is compliant with certain requirements: robustness of the response, computation time of the process, dimension of the design space, or the constraints to be fulfilled. From a methodological point of view, how to coherently choose the following must be found out:

- The objective function(s) to simultaneously or independently optimize: cost, mass, performance, payload, range of action, *etc.;*
- The design variables: accuracy of the geometric representation, discrete choices such as materials and equipment, macroscopic versus local representation, *etc.;*
- The coupling variables: variables that are used to link the various disciplines;
- The disciplinary analysis: number of phenomena to be included, level of assessment, inputs and outputs, *etc.;*
- The overall dependencies between disciplines and data exchanges: sequence of computations, local couplings, degree of freedom in the design, *etc.*

This requires knowledge about both the application at stake and the optimization techniques that will be used. This is why a mix between empirical and formal approaches must be used.

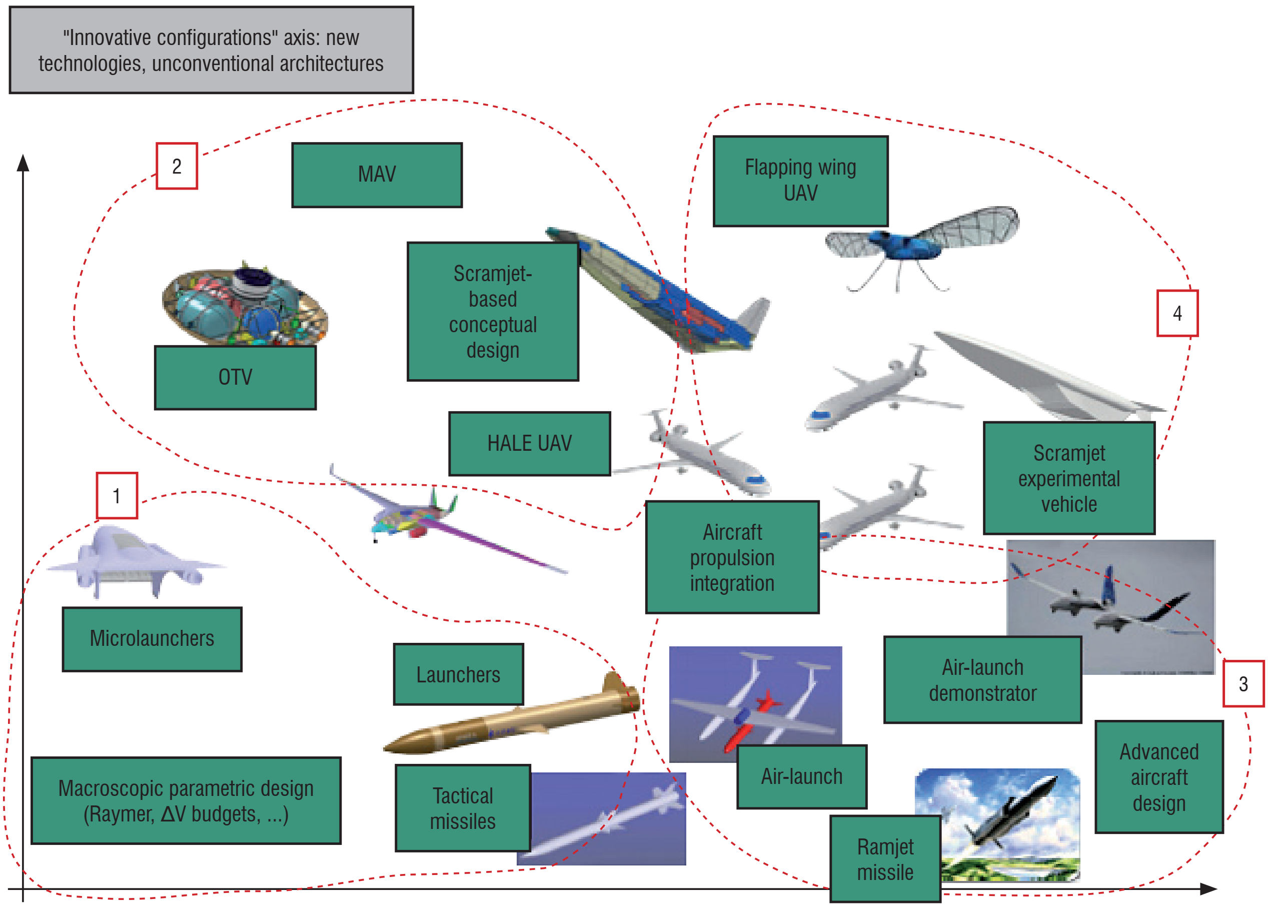


Figure 2 – Typology of design studies

Generic formulation of a MDO problem and classical MDO methods

Once the various previous choices have been made, incorporating the largest amount of knowledge possible to evaluate the design objectives and constraints, the next step is to formulate the problem, in order to be able to use suitable optimization algorithms.

The general formulation of an MDO problem can be written as follows:

Minimize $f(x,y,z)$

With respect to z

$$g(x,y,z) \le 0 \quad (1)$$

$$h(x,y,z) = 0 \quad (2)$$

Subject to

$$\forall i \in \{1,\cdots,n\}, \forall j \neq i, y_i = \{c_{ji}(x_j, y_j, z_j)\}_j \quad (3)$$

$$\forall i \in \{1,\cdots,n\}, R_i(x_i,y_i,z_i) = 0 \quad (4)$$

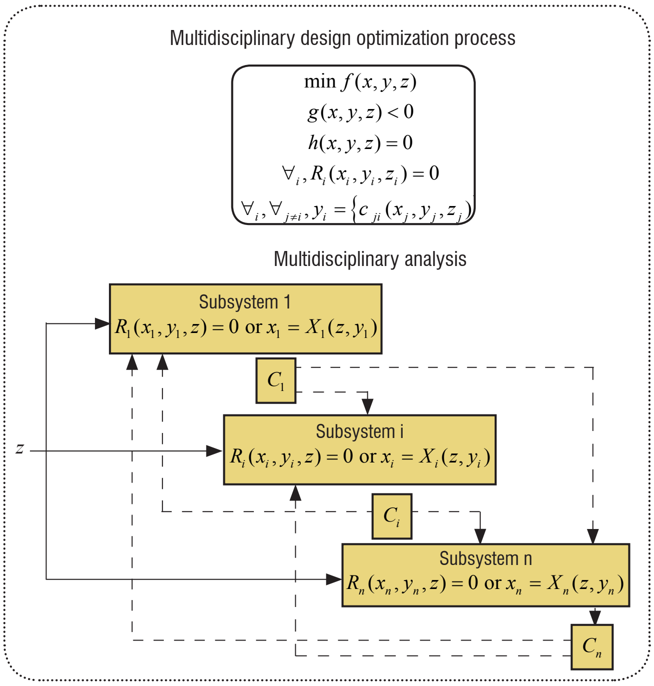


Figure 3 – General MDO process

A general MDO process is illustrated in Figure 3. This process involves several types of variables. These variables play specific roles and are regrouped into three categories:

- z: design variables. These variables change all along the optimization process, in order to find the optimal design. They can be used in one or several subsystems;
- y: coupling variables. These variables are used to link the different subsystems and to evaluate the consistency of the design with regard to the couplings c (equations 3);
- x: state (or disciplinary) variables. These variables can vary during the disciplinary analysis, in order to find equilibrium in the state equations (Disciplinary Equations 4). Unlike z, the state variables are not independent degrees of freedom, but rather depend on the design variables z, the coupling variables y and the state equations. The cases in which x are given by explicit functions of z and y are uncommon in engineering applications. The x variables are most often defined by implicit functions, which generally require specific optimization methods for solving complex industrial problems.

The disciplinary equations can be handled in different ways, using disciplinary analyzers (*i.e.* the subsystems are in charge of solving the equations 4 by the subsystems), disciplinary evaluators (*i.e.* the subsystems just compute the values of the residuals R in the equations 4) or a Multidisciplinary Analysis (*i.e.* the subsystem level is responsible for solving the coupling equations 3 and the residuals 4).

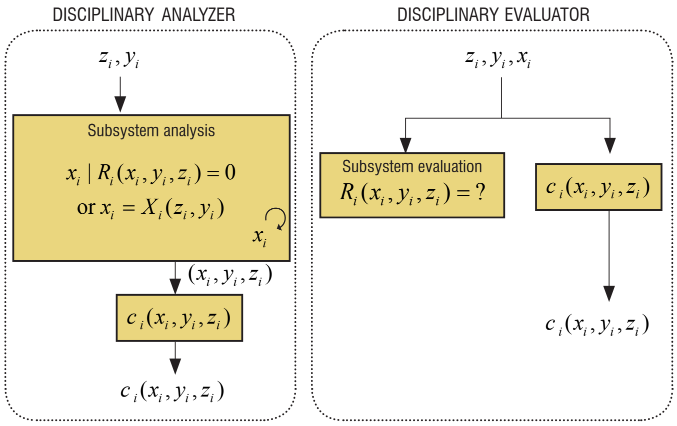


Figure 4 – Disciplinary analysis and evaluation

Many MDO methods are proposed in literature. The main methods can be grouped into two categories with respect to the use of one optimization level (MultiDiscipline Feasible MDF, Individual Discipline Feasible IDF, All At Once AAO [8], *etc.*) or multiple optimization levels (Collaborative Optimization CO [14], Bi-Level Integrated System Synthesis BLISS [63], Concurrent Sub-Space Optimization CSSO [66], Analytical Target Cascading ATC [46], *etc.*). [5] [65] can be consulted for more details regarding MDO formulations in aerospace design. The choice of the appropriate formulations depends on various characteristics of the problem to be solved, such as the search space dimension, the number of couplings, the disciplinary objectives, the availability of analytical sensitivity calculations, *etc.* Some papers (*e.g.* [69]) propose benchmark studies of the main MDO formulations in several test cases, in order to help the designer to choose which MDO formulation is the most appropriate for his problem.

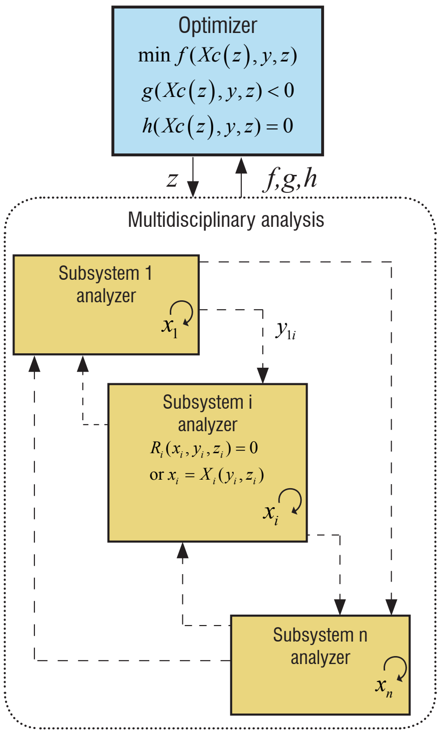


Figure 5 – MDF

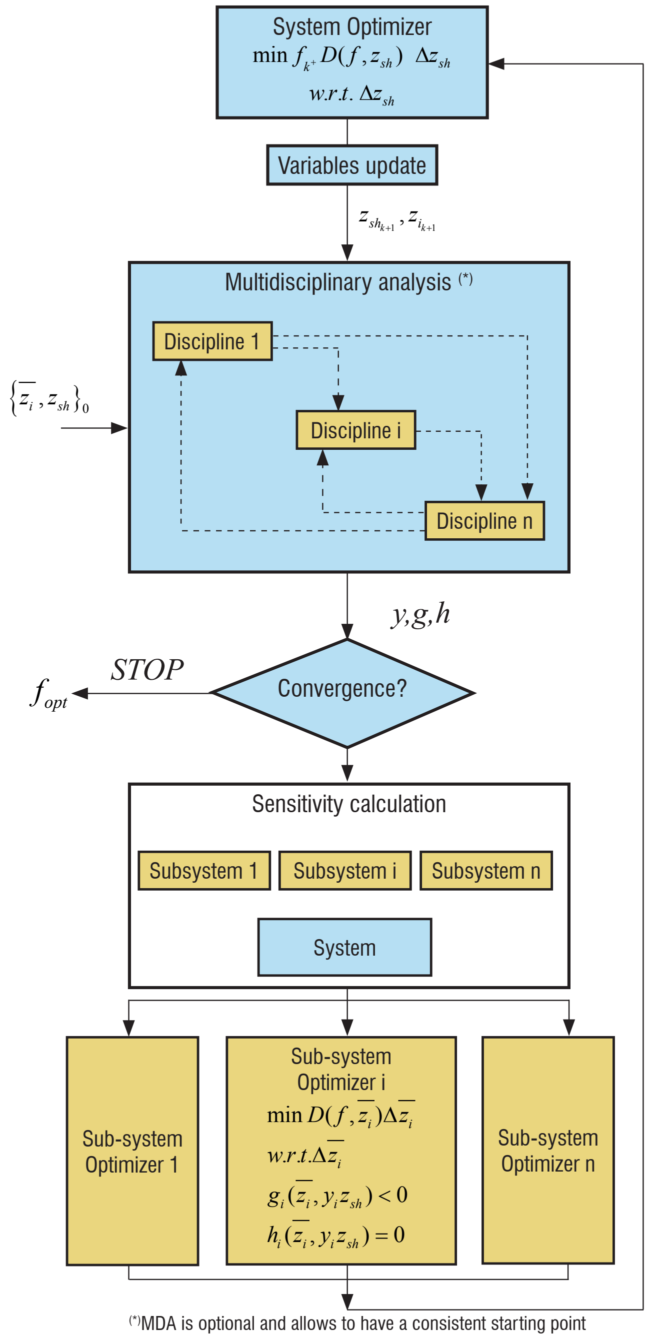


Figure 6 – BLISS

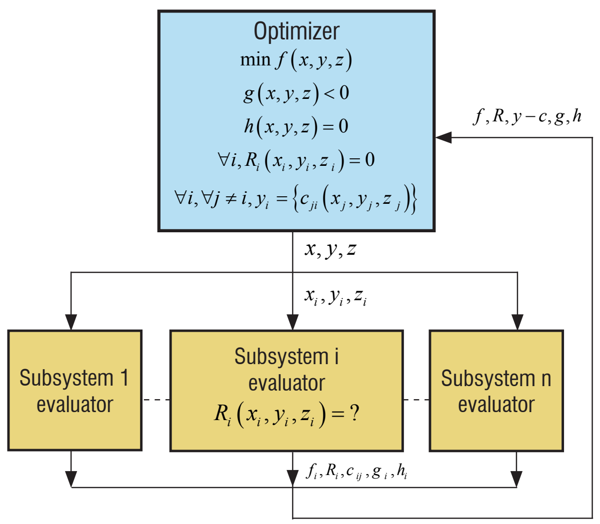


Figure 7 – AAO

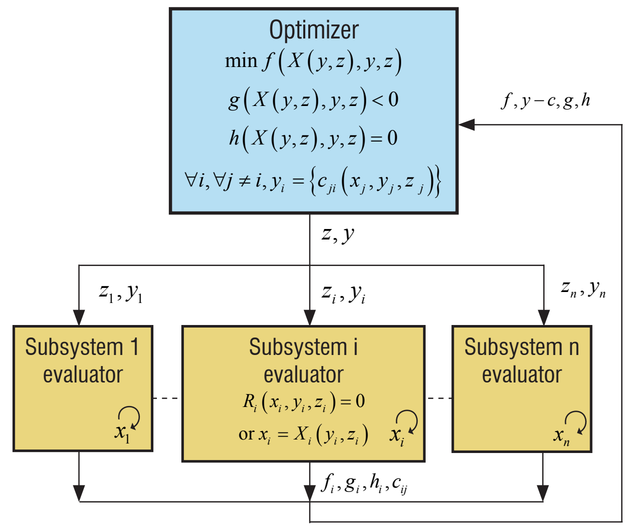


Figure 8 – IDF

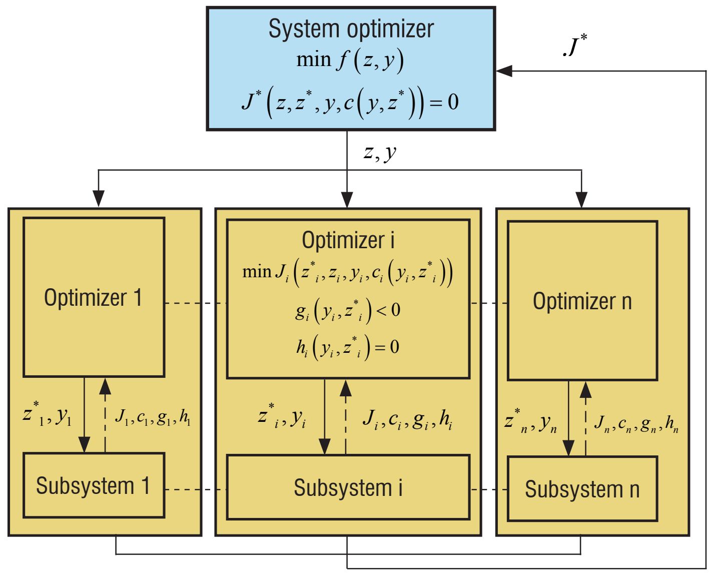


Figure 9 – CO

Some of these formulations have been compared, on a simplified Supersonic Business Jet aircraft design test case, in the frame of a PhD thesis at Onera [18]. These formulations have been compared in terms of convergence robustness, number of disciplinary calls and practical implementation difficulties. The analysis has shown that there is no preferred or universal approach for all types of problems, but a lot of knowledge could be accumulated to drive the choice for a new problem, depending on the requirements (discipline or interdisciplinary feasibility at each stage of the optimization process, convergence consistency requirements, natural structure of the MDA – mono or bi-level, possible use of global sensitivity equations, compromise between CPU time and accuracy, *etc.*). These formulations were also analyzed in the framework of a PhD thesis on launcher MDO (see the next section), for which new approaches were proposed.

Examples of application of some of the MDO methods described above (*e.g.* BLISS, CO and MDF) will be exposed in the next section. There are 2 extremes that should be avoided when performing the multi-disciplinary optimization:

- Optimizing the entire system by considering the Multidisciplinary Design Analysis (MDA) as a black box (which is known as the MDF formulation) is the most natural approach, but can be very costly if the

MDA convergence is difficult to obtain, especially when gradients need to be computed. No disciplinary expertise is included in that process;

- Optimizing the different disciplines separately and linking the disciplinary optimizations (Figure 10) is often the case in an industrial context, but disciplinary specialists tend to strive towards the improvement of objectives and fulfillment of constraints in terms of variables in their own discipline. This generates side effects that other disciplines must absorb, usually to the detriment of the overall system performance.

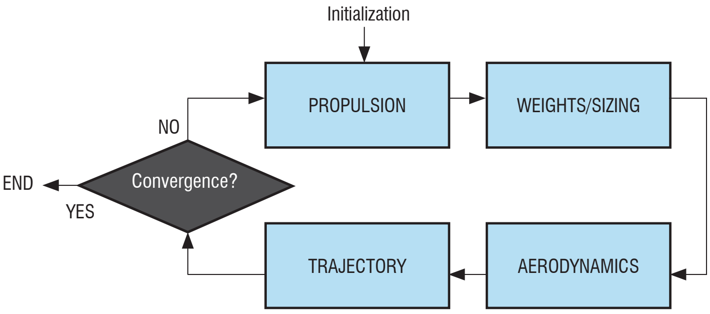


Figure 10 – Traditional design process

After having determined the most appropriate MDO formulation for the design problem, the suitable optimization algorithms for the problem must be selected. This is the subject of the following section.

Choice of the optimization algorithms

Basically, the optimization algorithms can be divided into two categories, with respect to whether or not they require sensitivity calculations. Since the presentation of the optimization algorithms is not the focus of the current paper, we only give a short description of these two categories.

The gradient-based methods are the most classical optimization algorithms. Basically, these algorithms consist in differentiating the objective function and the constraints, in order to adjust the variables. Complete descriptions of these algorithms can be found in [21][50]. A commonly used gradient-based algorithm is the Sequential Quadratic Programming (SQP) algorithm. For more details about this algorithm, [13] [27] [50] can be consulted.

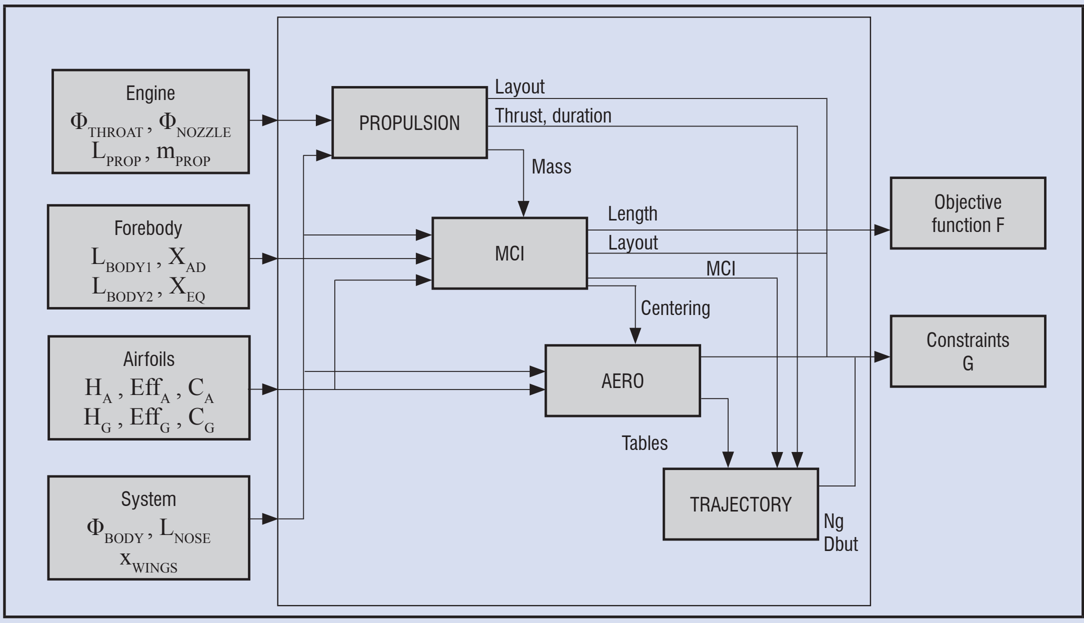
Gradient-free algorithms may present some interest in the MDO field, because the engineering (industrial) simulation codes may not have been designed to provide the sensitivity information in an efficient manner. Moreover, these algorithms allow non-differentiable and non-convex functions (and constraints) to be worked with, whereas the classical gradient-based algorithms require some differentiability and smoothness properties of the objective and the constraints. We can find many gradient-free algorithms in literature. The most popular algorithms are the Genetic Algorithm [28] [34], the Nelder & Mead algorithm [49], Simulated Annealing [38], *etc.* Several algorithms, such as Efficient Global Optimization [36], CMA-ES [31], may present some interest in terms of calculation time reduction and optimization efficiency in the search for the global optimum.

Integration of high fidelity tools: surrogate models

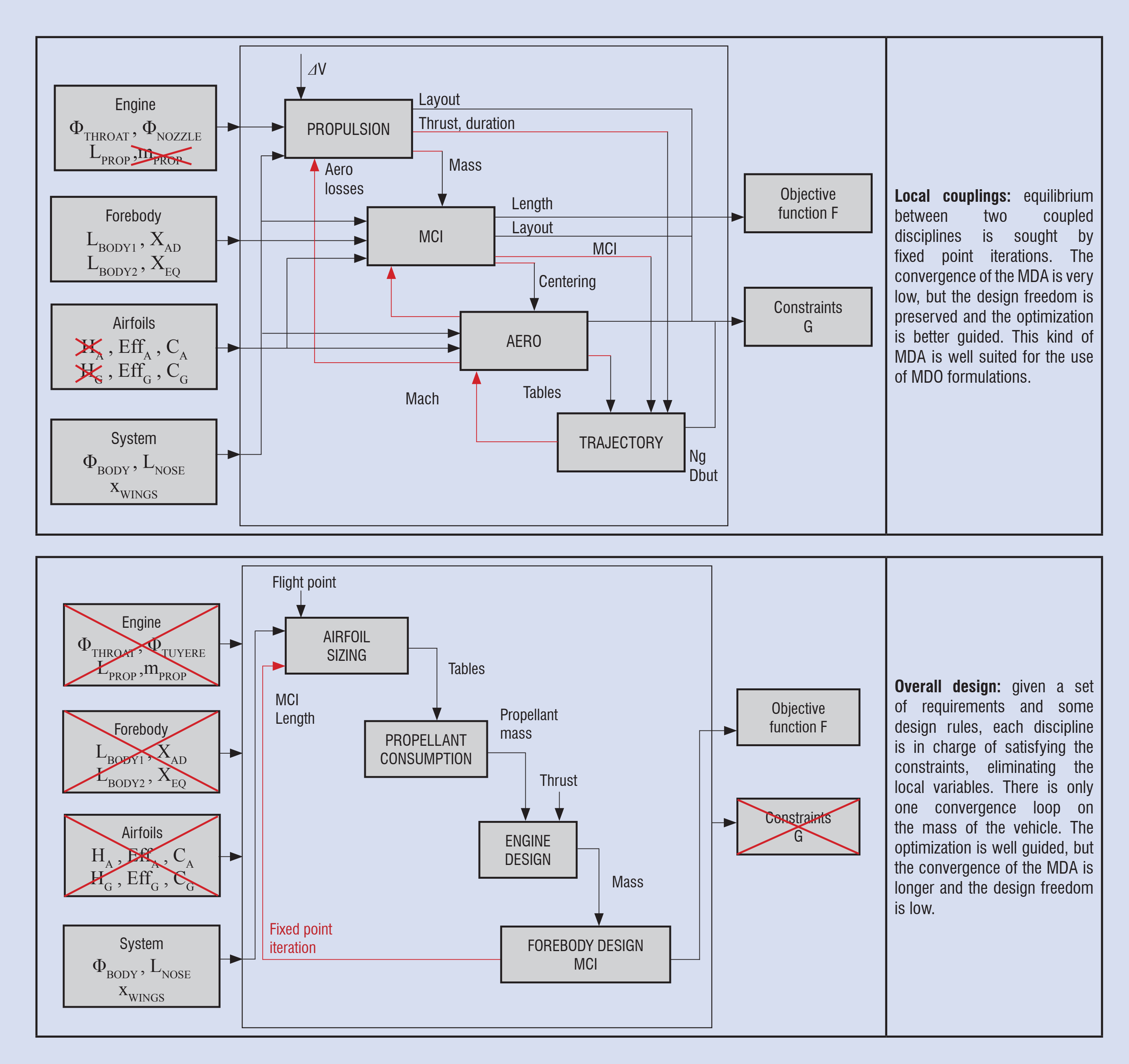
MDO formulations can provide better accounting for the interactions between disciplines. However, they also introduce the need, on the one hand, to automate the execution of each disciplinary code and, on the other hand, to have low computational cost models in the loop, which is in contradiction with introducing more knowledge at early steps of the design process. The challenge is then the smart use of the most advanced modeling tools, using response surface modeling to lower the computational cost [23] [73].

Box 1 - Typology of Multi-Disciplinary Analyses

When using an integrated Multidisciplinary Analysis, some key questions must be addressed, *e.g.*, how objectives and constraints must be computed, given a set of design variables and how must the couplings be handled? The answers to these questions are not unique and may have different consequences on the design process performance (time to converge, accuracy, degrees of freedom) depending on the coupling choices that are made (iteration loops, introduction of design rules at a disciplinary level, local variables calculated internally by the disciplines models, *etc.*). 3 typical processes are put forward:



Pure analysis: every design variable is free and the disciplinary models are run sequentially. Sizing and constraints satisfaction are handled by the optimizer. This allows a large exploration of the design space, but leads also to local minima and the task of the optimization algorithm is hard.



Reduced model

MDO is most often a time consuming process, whose cost increases with the number of design variables and the duration of the disciplinary evaluations. A common way to reduce this computational cost consists in substituting these high fidelity models by reduced models. These approaches could be classified by their method of construction. The reduced-order models (ROM) are based on the physical equations and complexity reduction is provided by simplifying assumptions, projection on a reduced basis [44], or substitution by a behavioral model. As long as they are sufficiently accurate, these models must be used preferably. Otherwise, when these models are not available or any more representative, the metamodels (also called surrogate models, regression model, or response surface models), exclusively based on some changes of the reference model, become an interesting alternative.

The polynomial regression [61] metamodeling techniques have benefited from the development of response surface methodologies [48] and more recently from the design and analysis of computer experiments with the Kriging statistical model [57]. Moreover, artificial neural networks [61], radial basis functions [35], splines [24], or support vector machines [24] from statistical learning have proved their efficiency in regression. All of these models could be classified by their degrees of liberty, the type of their basis functions and the learning technique. Consequently, their areas of application are not the same and their performances can be evaluated depending on these criteria:

• Implementation: the complexity of program implementation, method robustness and speed execution;

• Respect of physical problem specificities: bounds, strongly nonlinear behavior, symmetries;

• Quality of prediction: accuracy, consistency relating to size of design of experiments.

Metamodel construction

The construction of a metamodel requires three steps: selection, identification and validation.

• The selection step is aimed at selecting the set of simulation points and the most appropriate metamodeling technique. Since defining a representative experiment design is difficult for high dimensional systems, the reduction of the problem dimension should be studied. This can be done by selecting only the most influent parameters through a sensitivity analysis. The sampling of simulation points is crucial for the prediction quality of the metamodel and the robustness of its construction. For computer experiments, the design must be "space filling", that is, the simulation points must be evenly and adequately spread over the design of interest [39] to provide information from the complete design space. Depending on the final dimension and knowledge of the problem, adapted suitable metamodeling technique is chosen;

• Once the surrogate model is selected, its coefficients are the solution of a least square minimization problem whose complexity depends on the number of coefficients to be adjusted. This model fitting [61] uses samples reserved for the statistical learning, while another set is dedicated to validation tests and is in relation with the bias-variance trade-off, the result of the model parameter tuning compromise between learning and generalization samples;

• Finally, the evaluation of model prediction quality, evaluated by means of the model generalization error on the validation samples, allows the model to be validated or not. Statistical techniques, such as leave-one-out, cross validation or bootstrap, provide an estimation of this error.

The choice of the metamodel most suited to the problem can be made by having knowledge regarding the physical problem: input and output dimensions, behavior, number and location of samples and by fulfilling criteria, such as expected prediction accuracy or robustness of the construction. However, there is not always a cheap surrogate model able to satisfy all of these features. That is why many works dealing with the metamodeling technique, devoted to a specific problem, are under development. Since the best metamodel is the one that takes into account all of the available information of the reference problem, new approaches strive to integrate additional data, or a basis decomposition, linked with the problem in the metamodel construction.

Metamodeling for complex systems

A first example of methodology is the adaptive design of experiments, appropriate for expensive evaluations of the reference problem. The method consists in selecting new samples and updating the metamodel. The process is iterated until the desired error of the model is reached. These simulation points are chosen for their capacity to decrease the model uncertainty and result from an analytical expression of the model error, or statistical techniques like bootstrap [25]. Unfortunately, this approach is no more suitable for extremely costly evaluations of the reference problem. Recent methods are aimed at constructing models based on multilevel fidelity evaluations. Their purpose is to construct a surrogate model with many samples resulting from low fidelity evaluations corrected by a few high fidelity samples. Space mapping [9] constructs a matching function between a low fidelity model and a high fidelity model for correcting surrogate model evaluations in optimization problems. More recently, the construction of the Kriging model has been extended to samples of multilevel fidelity, using the space mapping technique. This co-Kriging model is described in [22]. Another illustration is provided by a strategy of trust-region model managing of the fidelity of surrogate models for MDO problems [54]. Multimodal problems require complex regression models involving a lot of coefficients. The resulting optimization problem can be very difficult and consequently requires a large set of samples. A mixture of experts combines several surrogate models that fit the clustered data set locally, rather than globally. Hence, the difficulty no longer lies in the construction of a global surrogate model, but rather in the domain decomposition and combination function.

Surrogate models for multidisciplinary optimization

Metamodeling techniques are particularly suited to MDO problems, in which discipline evaluations are costly and can be processed independently. In a general way, surrogate models are substituted into the disciplinary simulation [62]. However, the objective or constraints of the problem can also be approximated, in order to obtain the optimal point more easily. Moreover, the multilevel formulations were also adapted to the use of metamodels. Multidisciplinary feasible (MDF) formulations with the substitution of objective functions by metamodels are detailed in [37][60]. An extended formulation of BLISS to disciplinary metamodels is proposed in [67]. An adaptation of CSSO to artificial neural networks is detailed in [59]. An integration of moving least squares in the CO formulation is presented in [74].

High-fidelity modeling: surrogate model investigation

Within the framework of the DOOM methodological project carried out at Onera, significant research was made in regard to several RSM techniques, including neural networks, Kriging-based RSM, SVM, RBF, *etc.* These methods were applied on two test cases in the fields of structure (left) and aerodynamics (right), each being characterized by 5 parameters :

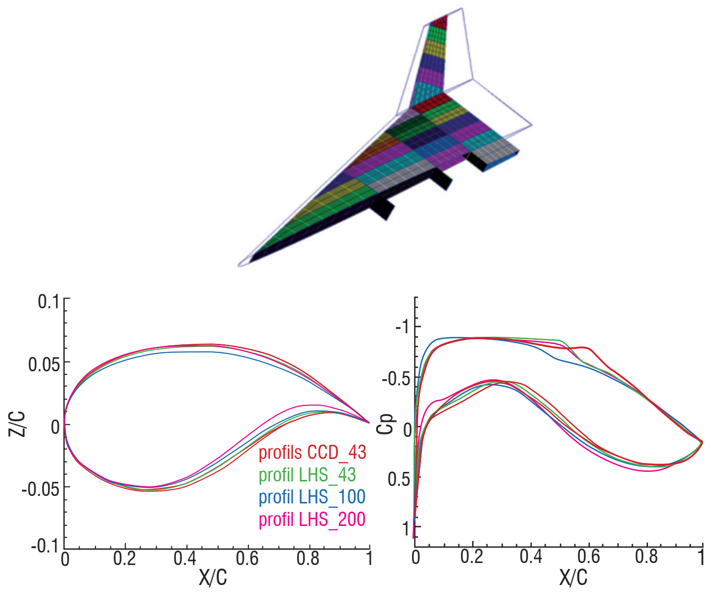


Figure 11 – Structure and aerodynamics, RSM test cases

The tests on 4 different kind of RSM with variable sample size showed the same behavior for both physics, which is illustrated by the chart on the right. It shows the error of the surrogate models along the X-axis and the percentage of validation points along the Y-axis, where the surrogate error is smaller than the X-axis error.

The Kriging methods appear to be quite efficient, but they are sensitive to the parameter tuning accuracy, RBF show acceptable results but little improvement is shown when the sample size increases and the neural network methods are difficult to tune, but offer greater degrees of freedom.

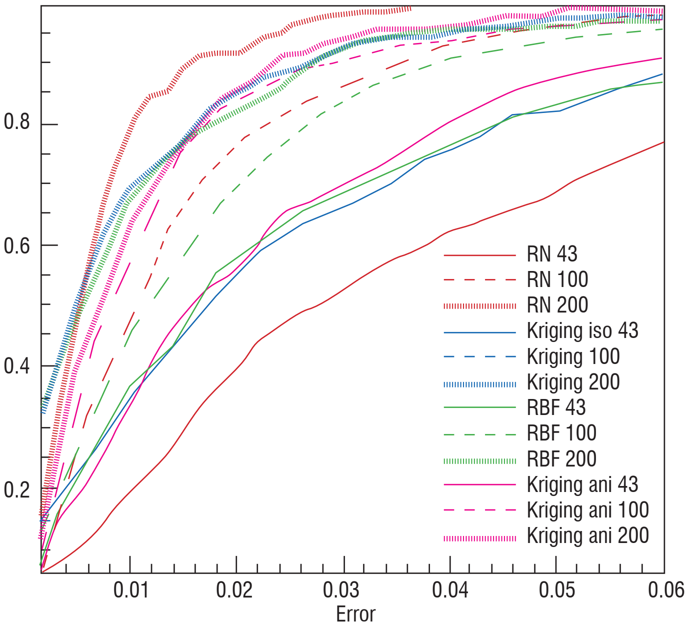


Figure 12 – Distribution of several surrogate models

Two examples of MDO applications at Onera

Many projects have been achieved at Onera involving the development of MDO techniques. For example, the construction of the UCoDe (UAV Conceptual Design) tool, inherited from the Onera project HALERTE. It consists in an integrated UAV design platform wrapped in the Model Center environment, which has been developed for 10 years through various studies. More details about this project can be found in [11][12][29][33][42]. This section is focused on two examples of recent use of MDO techniques at Onera: the design of aircraft and launch vehicles.

Aircraft design: the ARTEMIS project

Context

Airbus Flight Physics defined a strategy called Multi-Disciplinary Design Capability (MDDC) aimed at an enhancement of the aircraft development process, from the initial concept definition to the validation of the detailed product. The objective is to enable both a more robust design, based on a better knowledge of the aircraft (higher fidelity tools), and the possibility of keeping several design options [45] as long as possible.

To initiate the implementation of the MDDC in an industrial environment, Airbus started project ARTEMIS (Advanced R&T Enablers for Multidisciplinary Integrated Systems) to identify and complete the necessary technical progress to be made in different disciplines, as a first step, and then to carry out studies to increase the readiness level of these techniques. Launched in September 2008, the first phase, called ARTEMIS eXternal Research Forum (XRF), scheduled different workshops between European research centers (DLR, Onera, QinetiQ) in order to provide the state of the art in Multi-Disciplinary Optimization at different stages of the aircraft design process and the identification of the necessary scientific developments in 5 areas (data modeling, multi-disciplinary processes, optimization toolboxes, framework and tool integration). After several iterations between its specialists based on conclusions from past projects, Onera proposed at the end of ARTEMIS XRF a 5 years roadmap on the necessary steps to gradually implement MDDC. This roadmap is divided into two main research axes, and the part of the work performed at Onera is aimed at achieving the milestones identified for the first two years.

Bi-disciplinary bi-level design process

The Bi-Disciplinary process is aimed at optimizing the shape of the wing (planform, airfoil and twist) and its internal structure. The process is based on high fidelity tools used at the detailed design level. For CFD, elsA (Onera code) is used, while for CSM, NASTRAN is used. The architecture of this optimization process follows the BLISS approach. An asset of this method is the possibility to carry out the disciplinary optimizations in an independent manner. A general description of this method is given in the following figure, where:

- Xa correspond to Aerodynamic variables;
- Xs correspond to Structure variables;
- Z corresponds to system variables.

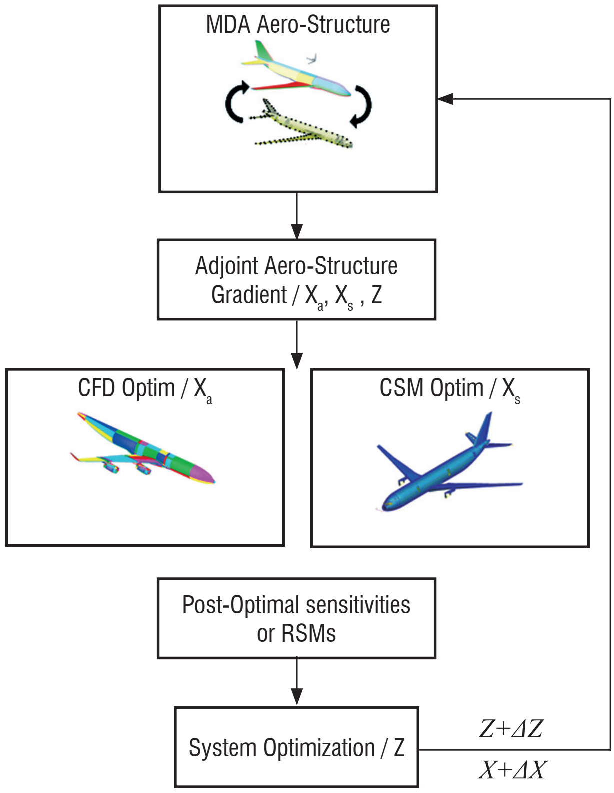


Figure 13 – BLISS approach into ARTEMIS project

In a first step, for a given set of disciplinary variables (X0) and system variables (Z0), the multidisciplinary aero-structure analysis is completed, resulting in a consistent set of data. Subsequently, the calculation of coupled sensitivities and the disciplinary optimization are carried out, resulting in a new set of disciplinary variables. Using post-optimal sensitivity analysis [14], the total derivatives with respect to system variables of the Drag and Structural Weight are evaluated. The optimization of the system with respect to the system variables is completed by a trust-region approach, to control the validity model of the reduced-model.

Global aircraft design process

This design process is aimed at performing the complete aircraft optimization (large number of disciplines involved and lower fidelity tools) at the conceptual design level (MG2 to MG3).

The constraints taken into consideration during this optimization process are:

- Limitations regarding the span, to meet airport constraints;
- Limitations on geometric parameters, to avoid unfeasible geometries;
- Approach speed;
- Take off field length considering a One Engine Inoperative (OEI) condition.

The multidisciplinary process of GAP is based on 4 modules, with strong interactions: aerodynamics (cruise configuration and low speed, from empirical equations), propulsion (thrust and specific consumption function of Mach and altitude, given by existing databases, or a rubber engine model), weight estimation (combination of fixed weights, empirical data and physics-based sizing) and mission performances (calculation of state variables over the whole mission). It is mostly based on aircraft conceptual design rules [54][55] and will also be aimed in the following steps at integrating the definition of the control system in the design loop [1][16][40][45][53].

A key point of the proposed roadmap is the introduction of a coupling between the Bi-Disciplinary Process and the Global Aircraft Process, in order to benefit from the assets of each approach and thus improve the respective optimization processes. Figure 14 gives an overview of the coupling between the two processes.

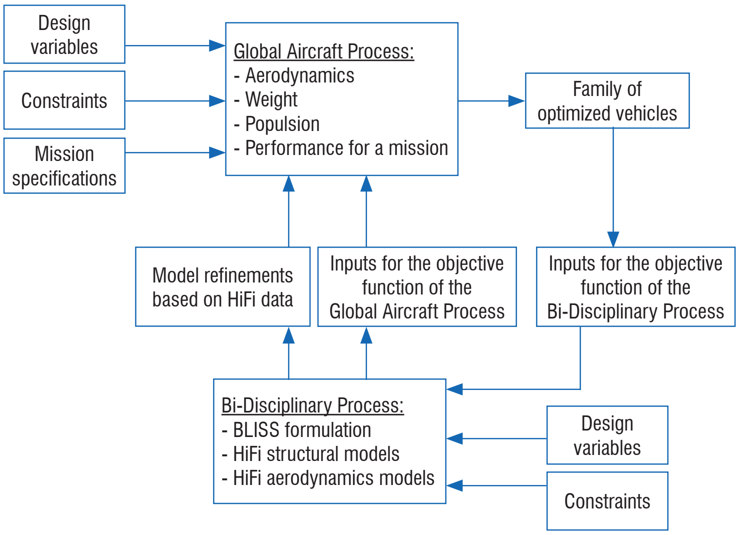


Figure 14 – Coupling between the Global Aircraft Process and the Bi-Disciplinary Process

MDO applied to launch vehicle design: SWORD method

Context

Launch Vehicle Design (LVD) is a complex problem, which involves many disciplines (propulsion, aerodynamics, structure, trajectory, *etc.*). These disciplines may have antagonistic objectives (*e.g.* structure and aerodynamics) and may require Multidisciplinary Design Optimization (MDO) methods to handle the couplings and to

Box 2 - Uncertainty handling

Uncertainties are becoming increasingly pervasive in the world of engineering systems. They can take, for instance, some random forms (operations, parameter-driven, shapes, physical model parameters) or epistemic descriptions (form driven, unknown unknowns). Uncertainty can consequently play a key role in designing the “best” engineering systems. Possible manners to use and characterize uncertainty in MDO are described next.

System and disciplinary analysis in MDO must be run thousands of times and involves a great computation burden. Approximation methods should be used to construct metamodels of the high-fidelity models and substitute them in the optimization, so as to balance the accuracy and cost [52]. To build approximation models, design-of-experiment (DOE) techniques [4][32] can be used, to sample data in the design domain with the knowledge of parameter uncertainty. The accuracy of the approximation models is dependent on the number of samples and on the positions of the samples in the design space. Nevertheless, too many samples could result in a computation burden in the construction of the metamodel itself. There is thus a trade-off between the sampling size and the metamodel accuracy.

Uncertainty analysis also allows the uncertainty distribution characteristics of the system performances under the impacts of design uncertainties to be described, and also determines which input parameters are the most influent on its performances. For complex systems with multiple disciplines, the direct propagation of uncertainties can be difficult to process for uncertainty analysis [51]. For that purpose, methods that could be used for uncertainty analysis are notably Monte-Carlo simulations [56], first order-second Moment analysis [72], stratified sampling, sensitivity analysis [68], *etc.*

Uncertainty can also influence the optimization process, such as the results based on first order reliability approximation in [43][47]. The first issue related to setting up the optimization problem is the selection of objectives. The output of the uncertainty model will be the mean and the stochastic distribution of each attribute. Therefore, it is straightforward to normalize these values, resulting in the mean of the performances and its distribution [30].

Uncertainty and design is becoming increasingly central to MDO and to decision making. New techniques in MDO that deal with uncertainty appropriately have the potential to impact many aerospace systems and problems of interest (*e.g.* [19][41][58][75][76]). Nevertheless, new approaches must be developed to make problems tractable and frameworks being developed today must take into account possible organizational structures dictated by design under uncertainty methods.

facilitate the quest for compromises. The most used MDO method in LVD is the Multidiscipline Feasible method (MDF). In this method, all of the optimization variables are handled at the same level, and a Multidisciplinary Analysis (MDA) is performed upon each iteration, ensuring the consistency of the couplings.

In order to decouple the computationally expensive MDA, classical decomposition used in LVD is performed according to the various disciplines. This decomposition makes possible the use of single-level methods (Individual Discipline Feasible, All At Once) or multi-level methods (Collaborative Optimization, Concurrent Subspace Optimization, Bi-Level Integrated Systems Synthesis, *etc.*). This discipline-wise decomposition does not exploit the main specificity of the LVD, which is the combination of the optimizations of the design and trajectory variables [5]. Indeed, the trajectory optimization is often considered as a black box and is optimized in the same way as for the other disciplines.

SWORD method

In order to place the trajectory optimization at the center of the optimization process, a new decomposition method, called the Stage-Wise decomposition for Optimal Rocket Design (SWORD) method, has been developed [6]. This bi-level method splits up the LVD problem according to the different flight phases and transforms the global MDO problem into the coordination of smaller ones. Each stage is optimized separately and the different stages are coordinated through the trajectory optimization, via the state vectors at the stage separations.

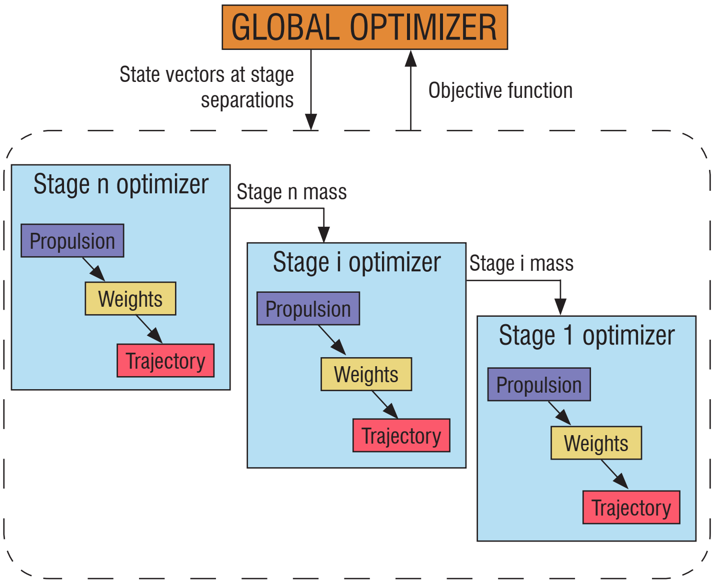


Figure 16 – SWORD architecture

Application case: optimization of a three-stage launch vehicle

The LVD problem to be solved is the optimization of a three-stage cryogenic launch vehicle. The objective function to be minimized is the Gross-Lift-Off-Weight (GLOW). The payload mass is equal to 4 tons and the target orbit is a Geostationary Transfer Orbit.

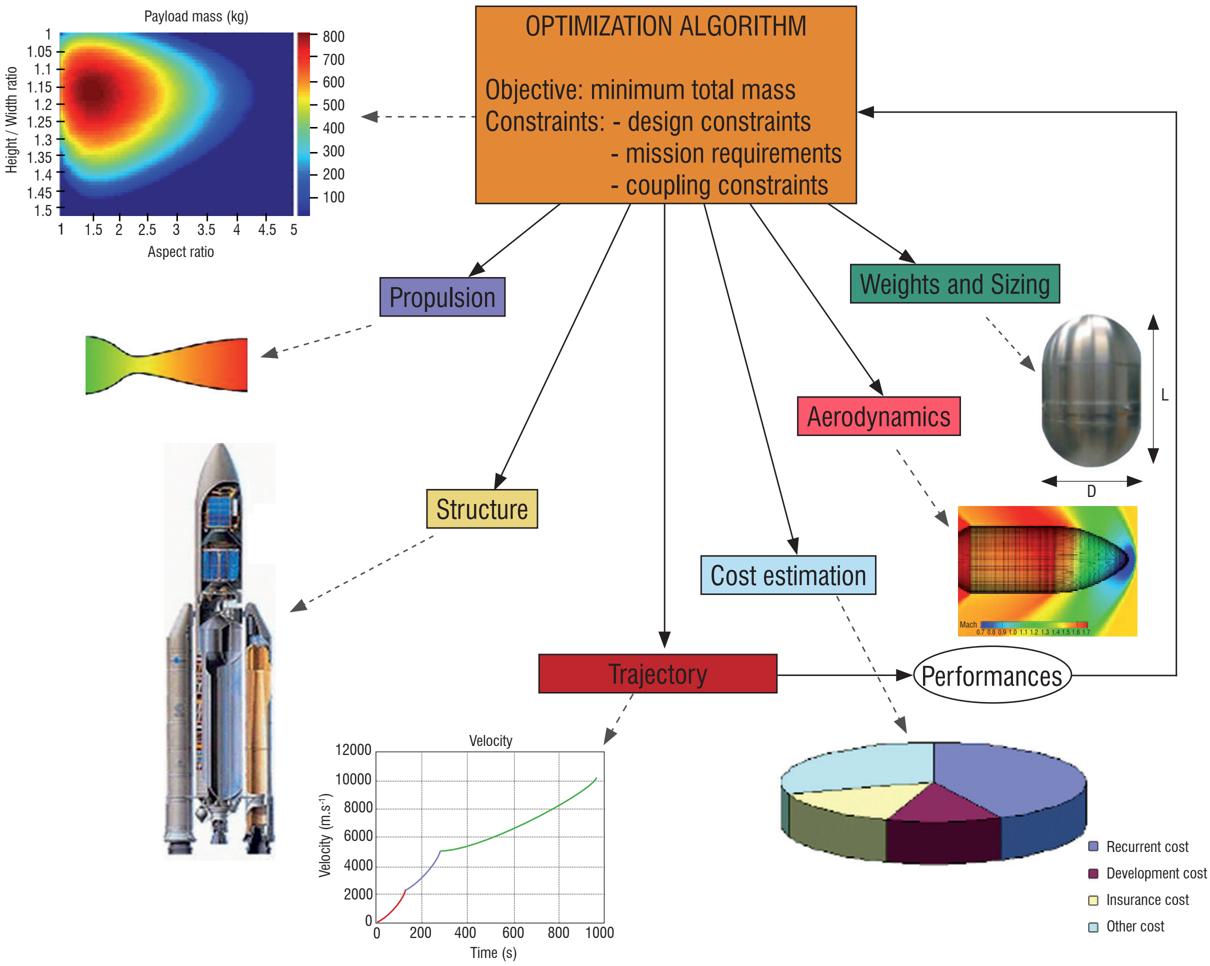


Figure 15 – Example of a Launch Vehicle Design process

Comparison with MDF in case of global search

In order to be consistent with the literature dealing with the MDO methods in launch vehicle design [10][17][20][71], the SWORD method has been compared with MDF using a same Genetic Algorithm in a very large search space. The comparison is performed considering the same computation time (10 hours). Ten runs have been carried out from random initializations and three comparative criteria have been selected for the comparison:

• The best found design at the stopping time of the algorithm;

• The time elapsed to find a first feasible design from random initialization;

• The improvement of the objective function during the optimization process.

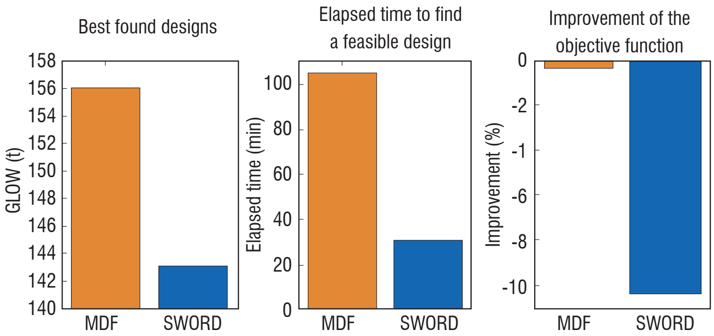


Figure 17 – Results of the comparison

SWORD clearly outperforms MDF in the case of global search optimization in a very large search space. Indeed, this method leads to the best design, is able to find a feasible design in a minimum time and leads to the best improvement of the objective function during the optimization. However, even though the SWORD method allows the efficiency of the MDO process to be clearly improved with respect to MDF, this study has shown that the use of a global search alone is not sufficient to obtain an optimum within an acceptable calculation time (a few hours). Therefore, the development of a specific optimization strategy is necessary.

Dedicated optimization strategy

Principle

The choice of the optimization algorithms is a key point in LVD. Indeed, both global and local searches are required, in order to explore a large search space and to converge efficiently toward an optimum. We have taken into account the four following requirements to develop the optimization strategy:

• The ability to quickly find feasible designs (*i.e.* satisfying the design and coupling constraints) from random initialization;

• The ability to converge from very large search domains (no accurate estimations of the optimization variables variation domains are required);

• Once a feasible domain is reached, the ability to efficiently converge toward an optimum.

In order to meet all of these requirements, we propose a three-phase strategy using the proposed stage-wise decomposition [7]. In the first phase, we exploit the flight-phase decomposition to perform a sequential exploration of the system-level optimization variable sets. Once feasible designs are found, a first optimization phase using the Nelder & Mead algorithm [49] is carried out to reach the vicinity of an optimum. Finally, in order to converge quickly toward an optimum, a bi-level gradient-based optimization, using Post-Optimality Analysis [14] and Global Sensitivity Synthesis [63], is achieved.

Results

In order to evaluate the efficiency and the robustness of the proposed optimization strategy, 10 runs have been carried out from different randomized initializations. The system-level variable search domains have been defined as very large, in order to estimate the efficiency of the method without requiring any a priori knowledge on design variables from the user. Figure 4 presents the change in the relative difference (in percentage) between the best found design and the reference optimum (which is obtained with fine tunings on the optimizers and design variable variation domains).

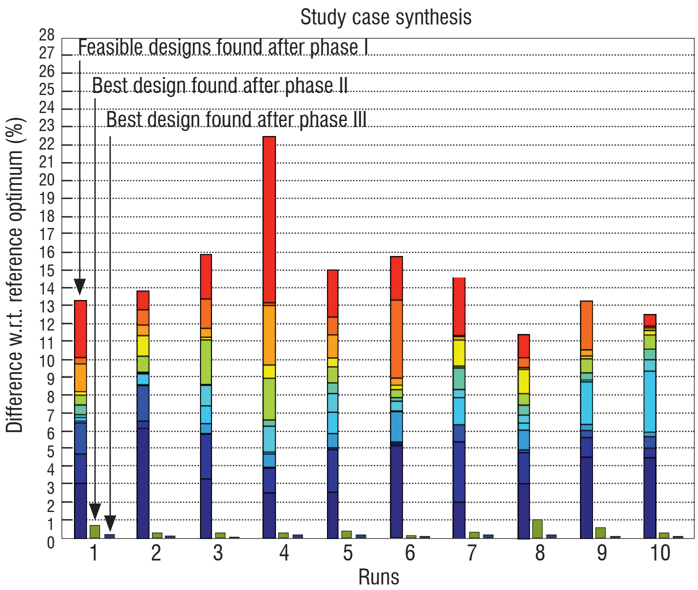


Figure 18 – Study case synthesis

The different divisions of colored left bars represent the 12 feasible designs obtained after Phase I, which are used to initialize the Nelder & Mead algorithm. In all of the cases, the optimization process converges with a maximal relative difference of 0.2% between the found design and the reference optimum. Indeed, the relative distance between the found design and the reference optimum is reduced by 96% on average, in a calculation time of approximately 4 hours (MATLAB, 2.4GHz Dual Core Pentium/Windows XP), which is very satisfactory in early design launch vehicle studies.

Conclusion and perspectives

Striving to achieve increasingly complex system integration studies and to generate innovative aerospace vehicle concepts, one faces the challenge of developing robust, efficient and innovative design methodologies. Comprehensive investigation of process set up, uncertainty quantification, high-fidelity tool integration and formal decomposition of the optimization strategy is mandatory, but this theory must always be tested and validated on 'real-life' design cases. The on-going methodological actions at Onera in the field of conceptual layout, control system design or RSM advanced techniques, together with the application in more and more industrial design cases, pave the way to a real "off the shelf" multi-level, multi-fidelity and multi-disciplinary capability ■

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Acronyms

AAO (All At Once)
ANR (Association Nationale pour la Recherche)
ARTEMIS (Advanced R&T Enablers for Multidisciplinary Integrated Systems)
ASMP (*Air Sol Moyenne Portée* / Medium-Range Air to Surface Missile)
ATC (Analytical Target Cascading)
BLISS (Bi-Level Integrated System Synthesis)
CMA-ES (Covariance Matrix Adaptation Evolution Strategy)
CO (Collaborative Optimization)
CSDL (Complex System Design Lab)
CSSO (Concurrent SubSpace Optimization)
DeDalus (Design of Dual-use Air Launch UAV Systems)
DOE (Design Of Experiments)
DOOM (Démarche Outillée d'Optimisation Multidisciplinaire)
FP7 (Framework Program 7)
GAP (Global Aircraft Process)
GLOW (Gross Lift Off Weight)
HALE (High Altitude Long Endurance)
HALERTE (Haute Altitude Longue Endurance des Robots Transportant des Equipements)
IDF (Individual Discipline Feasible)
LVD (Launch Vehicle Design)
MDA (MultiDiscipinary Analysis)
MDDC (Multi-Disciplinary Design Capability)
MDF (Multi Discipline Feasible)
MDO (Multidisciplinary Design Optimization)
OMD (French acronym for MDO)
OEI (One Engine Inoperative)
PERSEUS (Projet Européen de Recherche Spatiale Etudiant Universitaire et Scientifique)
SQP (Sequential Quadratic Programming)
RSM (Response Surface Methodology)
SVM (Support Vector Machine)
RBF (Radial Basis Function)
SWORD (Stage-Wise decomposition for Optimal Rocket Design)
UAV (Unmanned Air Vehicle)
UCoDe (UAV Conceptual Design)
XRF (eXternal Research Forum)

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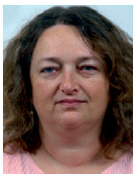

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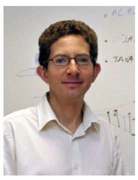

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An Overview of Probabilistic Performance Analysis Methods for Large Scale and Time-Dependent Systems

Various algorithms have been proposed to evaluate the performance of large scale and time-dependent systems. Probabilistic approaches based on computer experiments have been shown to be more efficient than classical approaches such as Monte-Carlo simulations for a various number of practical cases. This article thus gives an overview of the latest trends in the field, applied to the performance evaluation of large scale or time-dependent system. Different realistic applications in the aerospace domain are considered.

Introduction

In the aerospace and defense domain, realistic systems such as defense architecture or air traffic management are very time consuming and difficult to simulate with accuracy. Evaluating system behavior in order to improve performance or to evaluate alternative system design strategies thus requires system performances to be predicted for a given set of inputs or parameter values. To remain computationally feasible, this prediction requires a specific computational physics model, performance evaluation methods and uncertainty management.

In the context of model uncertainties, simulation tools are required to directly include uncertainty in system components and architecture, providing a set or a distribution of possible outcomes, rather than a single one. Uncertainty is considered as a measure of how large the deviations of a process from a predicted behavior can be. The classical approach consists in directly simulating the model using Monte-Carlo methods. A large number of samples of the parameter vector subject to uncertainty are randomly chosen, yielding a correspondingly large number of simulations, which may result in intractable complexity. Various alternatives have been developed to drastically improve crude Monte-Carlo performances.

This paper presents a review of a wide range of probabilistic methods that have been developed to estimate complex system performances. In the first section, Monte-Carlo methods are considered, since they can be applied in various frameworks. The last two sections describe alternative techniques that overcome some of the limitations of the Monte-Carlo approach.

Monte-Carlo approach

There are several approaches for taking into account parametric uncertainties within a system evaluation: interval analysis, fuzzy sets, fuzzy logic or possibility theory [1][29][107][22]. However, the probabilistic approach is the one that offers many powerful theoretical and numerical tools. The Monte-Carlo approach [83][85] is based on modeling each uncertain parameter through a random variable. The system then becomes a random parameter system and the output itself becomes a random variable $X(\omega)$, which must be characterized through its probability distribution $p_X(\omega)$. This may prove to be a very difficult task since there is almost never an analytical expression of the output distribution. The outcomes are usually statistical quantities, expressed as the mean of some output function $E\left[f(X(\omega))\right]$ derived from integrals again involving the probability distribution:

$$E\left[f(X(\omega))\right] = \int f(x)p_X(x)dx$$

The Monte-Carlo approach provides an estimation of this deterministic integral, by using repeated random samples: one does not need to know the output probability distribution as long as samples are available. This method is based on the Law of Large Numbers.

A natural and important question that arises is related to the convergence rate of this method. The use of the central limit theorem shows that the convergence rate is of order $\sqrt{n}$, where n is the number of samples. However, the convergence rate is independent of the size of the random variable, rendering this approach very efficient for high dimensional problems involving a large number of random $X(\omega)$ parameters. Another nice feature is that no smoothness assumption has to be made for the function f . The implementation of the Monte-Carlo approach is straightforward, since it acts outside of any given numerical code or procedure: one does not need to modify complex industrial codes, or even have any knowledge of them, in order to use it. This property is a key feature, which explains the popularity of the approach. The only requirements are, first, to be able to fit the probability distribution to each uncertain parameter introduced in the system and, secondly, to be able to generate random samplings for these distributions.

An alternative, known as Quasi Monte-Carlo methods, is to replace the random samples by low discrepancy sequences of numbers. However, error bounds are rather difficult to calculate and it appears that such methods should be used for a rather small number of uncertain parameters [69].

The effects of structural uncertainties have been studied in the aeroelastic domain for more than 30 years [74]. As an illustration of the standard Monte-Carlo method, let us consider the problem of evaluating the impact of the geometrical design defaults of an airfoil on the pressure distribution. Geometrical defaults are modeled as a Gaussian random deformation field acting along the airfoil. Figure 1 illustrates a particular simulated geometry.

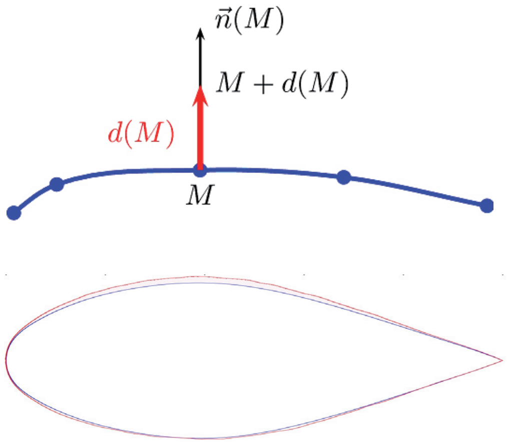


Figure 1 - Geometrical design defaults of an airfoil on the pressure distribution

Figure 2 shows the collection of results obtained by running the Monte-Carlo method with 200 samples of the airfoil geometry. From those results, statistics can be derived, such as the mean value and standard deviation of the shock position, as well as statistics on the stability of the fluid structure coupled system.

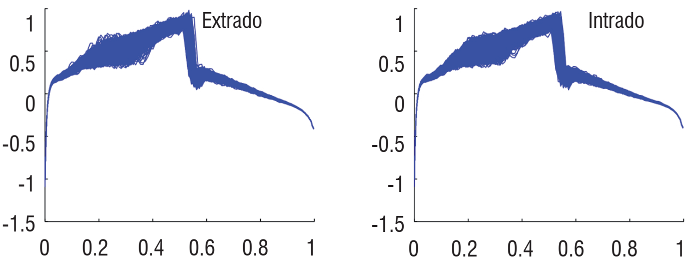


Figure 2 - Monte-Carlo estimation of the shock position

Due to their slow convergence rate, Monte-Carlo methods require a high number of samples. When accurate simulations are very time-consuming, surrogate models for representing the initial system or to assess the dynamic propagation of uncertainty are efficient tools for a limited computing budget. Estimation of very low quantiles may rule out a classical Monte-Carlo approach, since it would require too large a number of simulations

Black box system analysis

When only the resulting outputs are of interest, the black box model can be a crude description of the system. It is characterized by a certain number of input parameters and a few equations that use those inputs to give a set of outputs. This type of model is usually deterministic, so that the same outputs are always obtained for a given set of inputs. When the inputs have random behavior, different issues and questions can be raised. How can the system performance be evaluated if the simulation code is time consuming? What are the most influent inputs of a system on its output values? How can the uncertainty on the inputs be propagated? How can events with low probability (e; g. rare events) be generated?

Meta-modeling

A potential black box representation of a complex system can be supplied by surrogate models, such as response-surface methodology, Kriging, radial basis functions, splines or neural networks [43][93][104][26]. The idea is to substitute the evaluation of some simple function for the costly simulation of the complex system model, in response to a possibly high-dimensional vector of inputs [80]. For example, a prediction of the simulation value over a continuous space can be achieved by combining a space-filling sampling and an accurate interpolation meta-model over the space of interest. It is notably a very efficient strategy when simulation is time consuming. Figure 3 shows the fall-back positions of a space launcher stage, obtained with complex computer code or with a neural network learned from the complex computer code. Circles of Equal Probability (CEP) estimated in both cases are comparable, but the computation time is very low in the case of neural networks. Another application is the search for a global optimum of a criterion, computed via expensive simulation, by sampling only in promising regions of the search space. The surrogate model can then be adjusted accordingly to refine the estimate of this optimum.

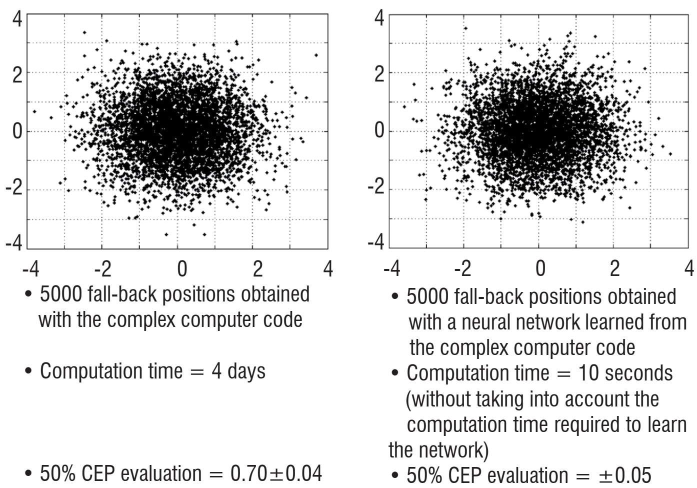


Figure 3 - Fall-back zone estimation of a space launcher stage

Among possible surrogates, Kriging [57][45] models the unknown function as a Gaussian process, which could be seen as the generalization of finite-space Gaussian distributions to a function space of infinite dimension. A correlation function is used to model the influence of the value of the function at one point on its value at another point, depending on a measure of distance between them. This correlation function and its parameters should be chosen according to smoothness assumptions on the function to be approximated. Based on these foundations, Kriging provides a continuous interpolation that is the best linear unbiased prediction of the unknown function. A very interesting property is the possibility to compute the variance of the prediction error at any predicted point, which can be interpreted as a measure of confidence in the interpolation (see figure 4 , for a simple one-dimensional example). Kriging can also be seen as a linear predictor with a weighted sum on a particular basis of functions, which corresponds to the prior chosen correlation.

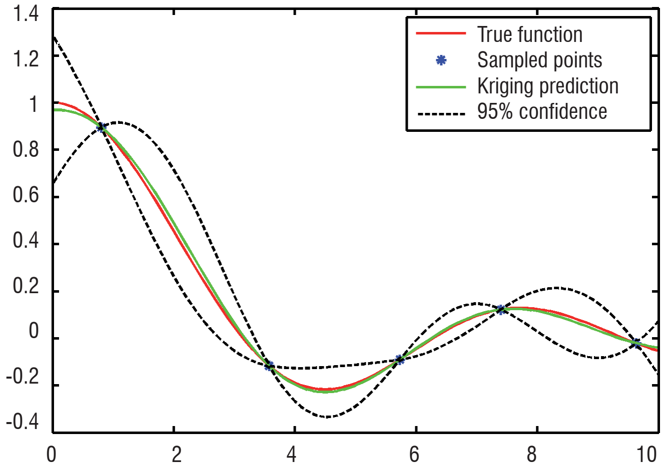


Figure 4 Kriging interpolation with 5 sample points

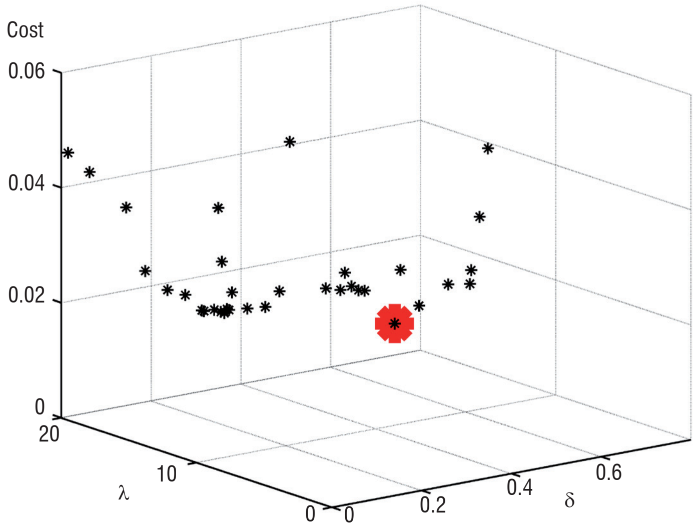


Figure 6 - Tuning of a fault diagnosis method with 2 parameters. The cost represents the trade-off between false-alarm and non-detection rates - exploration of the parameter space by EGO, the estimated optimum is in red

Moreover, the property of computing the confidence measure has been further exploited to design the so-called efficient global optimization (EGO) algorithm [43]. Its objective is to optimize a criterion, computed via a complex or unknown computer simulation, by iteratively sampling new points in the input search space, where the criterion should be evaluated so as to enhance the estimate of the global optimum.

This algorithm has been applied to various design problems, such as multidisciplinary design optimization [92], sensor analysis [62], active recognition [20] (see figure 5) and automatic tuning of fault detection methods [58] (see figure 6). This strategy has provided reliable results with very small samplings for the applications mentioned.

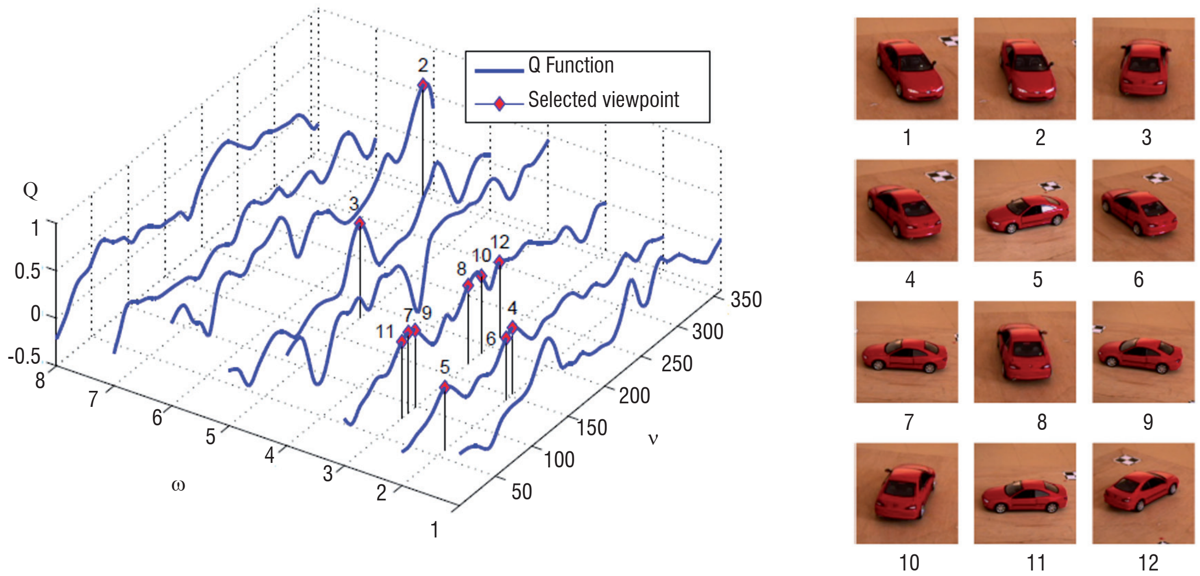


Figure 5 - Active recognition of car type from a database. For each class, the Q-function that determines the angle under which an agent should inspect a vehicle for better recognition has been obtained by Kriging and EGO

Box 1 - Design under uncertainty with Kriging

Available knowledge on uncertainties can be incorporated in different ways into Kriging models, to achieve robust design. In the case of noise on the output of the simulation to be approximated, a Gaussian distribution can be taken into account through the covariance that is at the basis of the Kriging prediction [81]. The resulting linear prediction incorporates the amount of noise to build a smooth fitting function and is thus no longer an exact interpolation of the data. This makes it possible to work with a filtered model from noisy observations, at a low computational cost [100].

For optimization purposes, a generic model is to consider that the computer model under study depends on two types of inputs: control variables and environmental variables [88]. The control variables are those on which optimization is carried out, while the environmental variables are uncontrollable disturbances that affect performance. For instance, a control law or an estimation filter for an aeronautical vehicle are subject to measurement noise, strong uncertainty on the model parameters, variations of the atmospheric conditions (temperature, pressure) and wind turbulence. In such a case, a design of the control variables that is robust to the effect of these environmental variables is sought. When dealing with robust design, a probabilistic or deterministic point of view can be adopted [4]. In the probabilistic framework, a distribution of the environmental variables is assumed and performance is assessed by the expected value of some robustness measure. However, a design that is good on average may prove to be poor for particular values of the environmental variables. In the deterministic framework, it is assumed that the environmental variables belong to some known compact set and performance is assessed by the worst possible value of some robustness measure. The design that is best in the worst case is obviously conservative on average, and the choice between the probabilistic and deterministic points of view should be made on a case-by-case basis. In the probabilistic context, some papers have addressed robust Kriging-based optimization with respect to environmental variables.

In [11][53], Monte-Carlo simulations are performed for each sampled value of a space-filling design of the control variables and a Kriging model is fitted on the resulting mean and variance, before achieving optimization by classical algorithms. In [54], the EGO algorithm has been extended to take into account a probability distribution for the environmental variables. The underlying idea is to minimize a weighted average of the response over a discrete set of values for the environmental variables.

In the worst-case context, an algorithm has been proposed in [59] to deal with environmental variables for the robust optimization of black-box functions evaluated by costly computer experiments. It combines EGO with an iterative relaxation procedure, to provide an algorithm for the minimax optimization of black-box functions. Relaxation makes it possible to take into account continuous infinite spaces for both the control and the environmental variables, unlike the discrete probabilistic formulation mentioned before.

All of these algorithms have shown promising results and are especially well suited when a robust design is required for an expensive-to-simulate process, unlike most global-purpose optimization algorithms that require a thorough exploration of input spaces.

Sensitivity Analysis

Using black box or surrogate models, determining what the most influent inputs of a system on its output values are remains a key point. This sensitivity analysis deals with how the uncertainty in the output of a statistical model can be linked to different variations in the inputs of the model. Figure 7 illustrates an example of sensitivity analysis, applied to the study of space launcher stage fall-back positions. The color of the different samples varies with the input value. Inertial measurement appears to be the most influent factor on the fall-back position. Sensitivity analysis methods allow quantitatively similar results to be obtained in a rigorous manner. Two main approaches have been developed for that purpose.

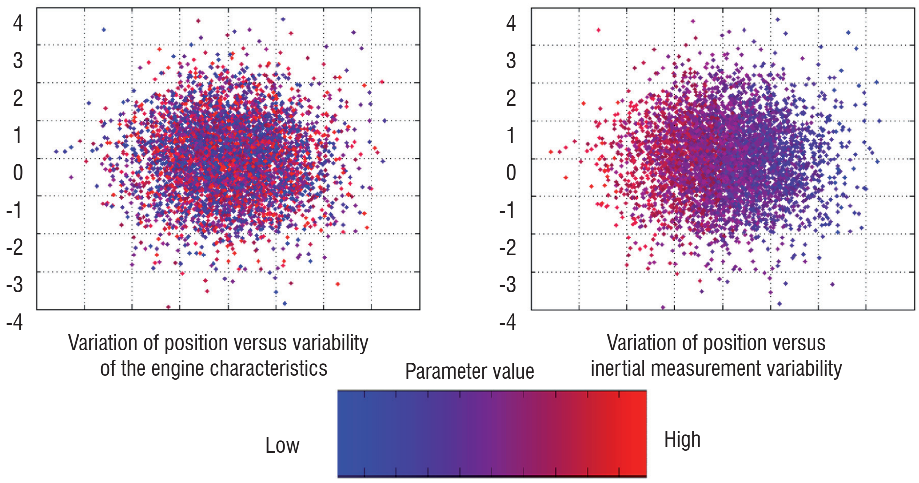


Figure 7 - Influence of two inputs on fall-back positions

Global sensitivity [40][96][87] analysis focuses on the variances of model outputs and more precisely on how the input variability influences the variance of a given output [38]. It makes it possible to determine which parts of the output variance are due to the different inputs, with the estimation of Sobol indices (see e.g. [95][86] for a detailed description). They are major tools in sensitivity analysis, since they give a quantitative and rigorous summary of how the different inputs influence the outputs.

Local sensitivity [67][1][79] analysis provides information on how small perturbations in a neighborhood of an input space value influence the model output value. Since local sensitivity analysis is not robust to non-linear effects and input interactions, it is often less used than global sensitivity analysis. Moreover, a global sensitivity method makes it possible to take into account the interaction between input values. Nevertheless, the local sensitivity analysis method has the advantage of requiring fewer simulations than the global method, when running the model is very time consuming.

Uncertainty propagation

Uncertainty representation under the form of a probability density function has been exploited in several methods for analyzing and propagating uncertainties in systems, such as interval analysis, Monte-Carlo and quasi Monte-Carlo techniques. However, none of these approaches is able to allow for the intrinsic nature (in terms of continuous random distributions) of the assumed stochastic uncertainties. To fill this gap in many methodologies, the Polynomial Chaos Theory (PCT) has been recently used to tackle this problem. This theory is based on the principles stated initially by Wiener in 1938 (see [106]) and then justified by Cameron and Martin in 1947 (see [7]). More recently, further research work has shown the effectiveness of the PCT in many engineering applications subject to stochastic uncertainties, such as mechanics, heat convection, fluid dynamics or automatics [24][30][55][103]. A recent wide survey of the theoretical background, including some practical results of the PCT, is available in [99]. The basic idea of the PCT consists in modeling any probabilistic uncertain system (static or dynamical) as an equivalent deterministic one, in a higher dimensional space, where the explanatory variables of the initial stochastic model are decomposed on a Hilbert basis of L^2, generated by the polynomial representation adopted to approximate any uncertainty of interest. This theory is a powerful alternative to Monte-Carlo and/or quasi Monte-Carlo methods in propagating probabilistic uncertainties and estimating more accurately the properties of any stochastic static or dynamical system, in terms of mean and variance.

An illustrative application of the PCT is provided in figure 8 , in which an AIRBUS A340-600 lateral flight dynamics linear model has been expanded over 3 uncertain aerodynamics derivatives. This figure compares the poles dispersion of the natural modes of the aircraft obtained by both Monte-Carlo and PCT methodologies and shows the relevance of the PCT for estimating the probabilistic properties of stochastic systems. In addition, the application of the PCT using Galerkin projections presents a significant computational advantage over Monte-Carlo and quasi Monte-Carlo methods.

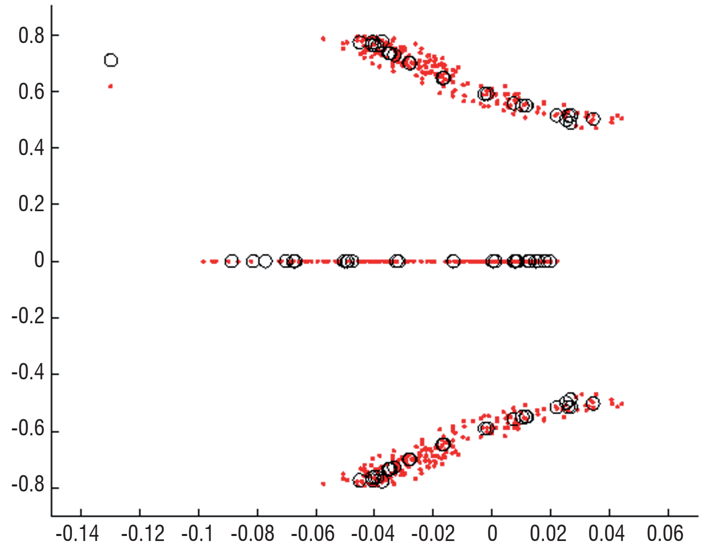


Figure 8 - Pole dispersions for Dutch Roll and Spiral stability modes Comparison between Monte-Carlo and PCT

Rare event estimation

Monte-Carlo or quasi Monte-Carlo representations are well suited for providing information on events whose associated probabilities are not too low. For very seldom observed events, such as the collision probability between two aircraft in airspace, these approaches do not lead to very accurate results. Indeed, the number of available samples is often insufficient to accurately estimate such low probabilities (at least 10^6 samples are needed to estimate a probability of order 10^{-4} with 10% relative error). It is therefore necessary to develop appropriate techniques to estimate these probabilities, requiring a fewer number of samples. They can be divided mainly into two categories: probability density function tail parameterization techniques based on extreme value theory and simulation techniques such as importance sampling or importance splitting.

Extreme value methods are very useful when it is not possible to obtain, or simulate, new samples. Finance [31] is the main domain of application of the extreme value theory, but some applications have also been proposed in the world of engineering [73]. There are two main kinds of model for extreme values. Block maxima models [25][52][19] are notably used for the largest observations collected from a high number of identically distributed observations. It allows the law of the maximum of a sample collection to be determined. A more recent group of models is the peaks-over-threshold (POT) approach [18][60][72]. It allows the law of the samples to be determined conditionally to exceed a high threshold. POT models are generally considered to be the most useful for practical applications, due to their more efficient use of the (often limited) data on extreme values.

Simulation techniques require the ability to simulate new samples. Importance sampling is the most well-known rare event simulation technique. It is designed to reduce the variance of the Monte-Carlo estimators for a given sample size. Importance sampling consists in generating random weighted samples from an auxiliary distribution rather than the distribution of interest. The crucial part of this algorithm is the choice of an efficient auxiliary distribution that must be able to simulate additional rare events. Various optimizations of auxiliary distributions have been described in [39][84][14][56][109][66][63]. Figure 9 shows different iterative importance sampling auxiliary densities for the $(1\text{-}10^{-7})$-quantile estimation of a centered reduced Gaussian density. The principle of importance splitting [47][9][8][64] is quite different. Instead of estimating one probability through a very costly simulation, one considers the estimation of several conditional probabilities that are easier to evaluate by simulation. The sought probability is then obtained with the use of the Bayes theorem. Importance splitting is notably very adapted when the simulation budget is important and the probability to be estimated is very low ($<10^{-6}$).

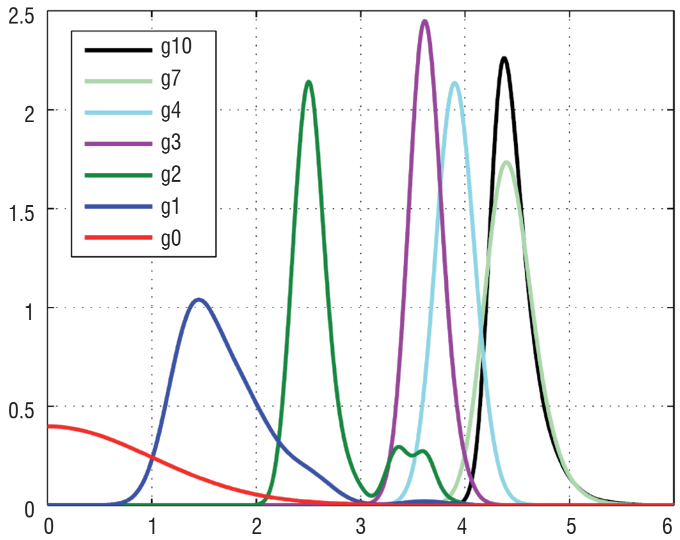


Figure 9 - $(1\text{-}10^{-7})$-Quantile estimation of centered reduced Gaussian variable with non-parametric adaptive importance sampling

Application areas of rare event estimation methods in reliability and safety engineering are very broad and are not restricted to aerospace. Among the applications currently dealt with at Onera, figure 10 illustrates the fall-back zone estimation of a space launch vehicle [65] and figure 11 presents the collision probability map estimation between aircraft in uncontrolled airspace with rare event methods.

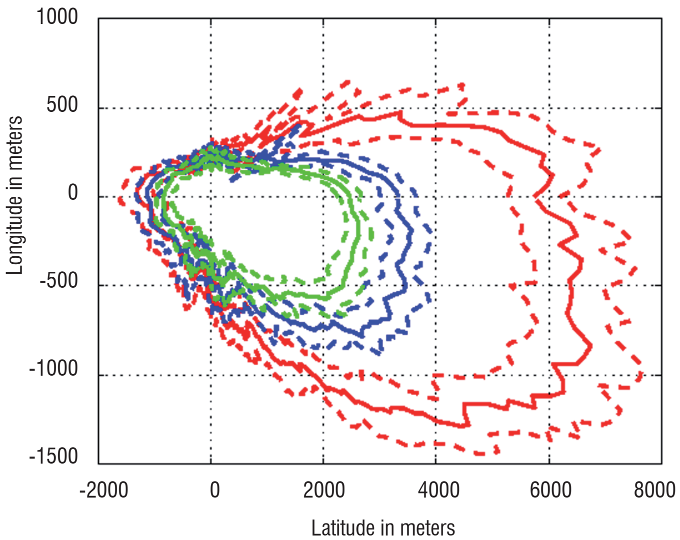


Figure 10 - Mean (solid line) and standard deviation (dashed line) of a launcher stage fall-back zone with importance sampling simulations (95 % =green, 99% =blue and 99.99% =red)

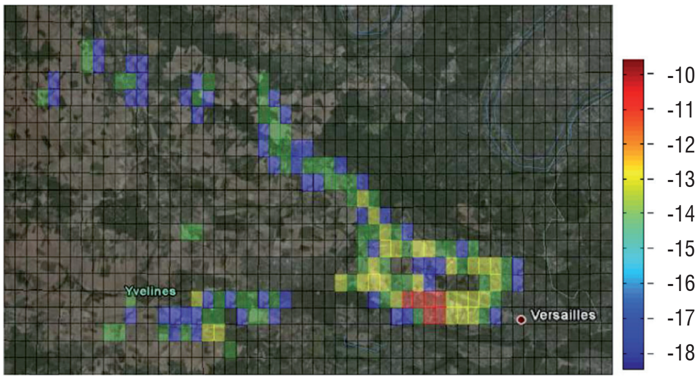


Figure 11 - Map of collision probability estimates with importance splitting. The color scale depends on the logarithm of the probability

Box 2 - Estimating satellite versus debris collision probabilities via the adaptive splitting technique

Spacecraft collision still does happen seldom, but the loss of a satellite cannot be afforded. This high risk therefore must be addressed carefully. To support the decision to start a collision avoidance maneuver, a dedicated tool is the probability of collision between the debris and the satellite [44]. Crude Monte-Carlo could be a way, if it could cope with very small probabilities, say 10^{-6}, within the available simulation budget and time. The methodology in use nowadays is a numerical integration made tractable by physical hypothesis and numerical approximation [10]. An efficient alternative is to consider an importance splitting technique, since this avoids the different hypotheses needed for the numerical integration and clearly outperforms CMC with respect to rare events, as is illustrated in table B2-01. However, importance splitting requires tuning. Some experience based empirical tuning rules are notably proposed in [71].

	Collision probabiity estimate (relative error)	Mean sample number
Monte-Carlo	$1.1\ 10^{-6}$ (172%)	300000
Importance Splitting	$1.9\ 10^{-6}$ (32%)	309000

Table B2-01- Importance splitting-Monte-Carlo comparison

Time-dependent system analysis

Performance evaluation can also be sought for a time-dependent system. Examples of such systems include the weather evolution, stock market, plane trajectories. In the following, different methods to deal with time-dependent stochastic process of complex systems are presented.

Multi-model representation for performance analysis

The first approaches for characterization and analysis of dynamical system performances have been derived from the safety literature. Most of them are based on combinatorial approach such as fault or event trees or reliability diagram (see e.g. [42][82]). Using these methods allows the combination of events that lead to a specific system behavior to be identified. However, basic fault trees are not well suited for modeling complex systems with strong dependencies between the system components. The assumption of component independence is a powerful feature of fault trees, but is extremely restrictive and may lead to erroneous results.

In order to provide a realistic evaluation of the system performances, the model should include a representation of the dynamical interaction between its physical parameters and the functional behavior of its components. In the 80's, Davis presented the Piecewise Deterministic Markov Processes (PDMP) [15][17][16]. This class of models constitutes a well-suited framework to represent dynamical systems subject to (expected or unexpected) changes in their behaviors. The description of the system is provided in the form of a set of small models, each related to a different operating behavior mode [108]. The representation is based on two types of variables, one representing the dynamical states of the system and the other representing the mode, usually with discrete values. The states are used for the deterministic representation of the system evolution, whereas the mode indicates the suitable characterization of its behavior. The change in the functioning is reflected in the modification of the mode value.

Representing a complex system under this form requires, firstly, to split it into subsystems or components. It is then possible to identify all of the possible regimes and dynamical models for the subcomponents and to define whether the change of mode from one behavior to the next is deterministic or probabilistic. The probabilistic jumps can be modeled using a Poisson law and the deterministic jumps are obtained for a given time, or when the state components satisfy a predefined criterion. Given a time period, it becomes possible to simulate the whole trajectory of the entire system. Evaluating a performance criterion is then performed by simulations, based on indication on the characteristics of the Poisson law and the modeling of the piecewise deterministic representation. This modeling can also be used to determine suitable control, for example, for reconfiguration purposes [13].

Markov Chain

Another representation of the dynamic evolution of a random process is a Markov chain, which consists in a collection of random variables (X_n where n is a positive integer)[17][61]. Namely, if X_o is the initial state of the process, X_n represents its state at the n^{th} step, the result of n random moves (transitions) in the state-space. In engineering applications, steps are usually taken as a measure of time.

A Markov Chain usually refers to a discrete random process, with the Markov property stating that the conditional probability distribution for the system at the next state, given its current state, depends only upon the current state (i.e. the process has no memory). If P is the probability distribution for the system at a given state, to move to the next one (the transition probability), the following relation holds (according to the Markov property):

$$P\left(X_{n+1}=x_{n+1} \middle| X_1=x_1,\dots,X_n=x_n\right)=P\left(X_{n+1}=x_{n+1} \middle| X_n=x_n\right)$$

A Markov chain is fully characterized by its state-space and transition probabilities.

Among specific properties, usually highlighted, a Markov chain is said to be irreducible if it is possible to get to any state from any state; it is said to be k-*periodic* if any return to a given state occurs in multiples of k steps; a state is said to be *transient* if the probability that the trajectory of the random process starting from this state has a non-zero probability of never going back to this state (otherwise, the state is *recurrent*); a state is said to be ergodic if it is aperiodic and recurrent (with a finite mean recurrent number of steps).

Finally, it is usually impossible to predict the exact trajectory of a Markov chain, since it is a random process, nevertheless in specific case it is possible to predict the statistical properties of the Markov sequence. For example, an irreducible and aperiodic Markov chain will reach a stationary probability distribution $\pi(i.\ e.\ X_n \sim \pi)$. Many algorithms allow Markov chains with the desired statistical properties to be constructed, thus offering the ability to generate sequences of random numbers that reflect targeted distributions. These processes (namely Monte-Carlo Markov Chains) have been very useful in Bayesian inference and many other fields. An example of a Markov chain is given in figure 12 to analyze the random trajectory of a commercial flight [41][78].

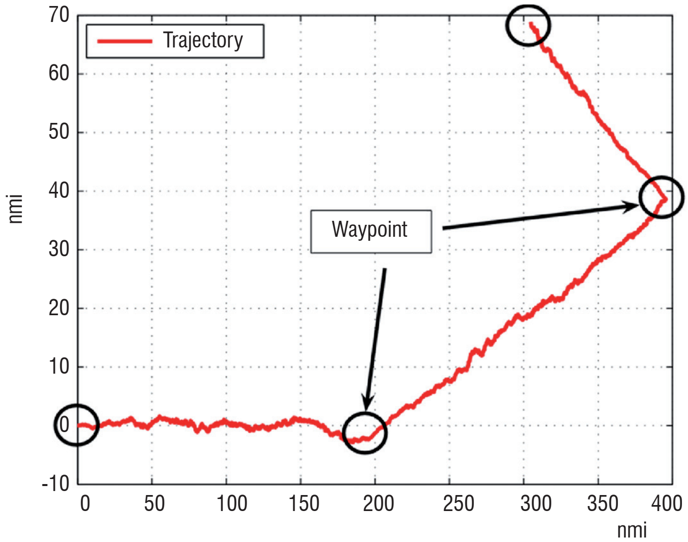


Figure 12 - Commercial flight trajectory modeled with a Markov chain

Bayesian Networks

The Bayesian Network (BN) theory is a formalism based on the Graph Theory and the Bayes probabilistic Theorem. It is used for representing systems or entities in a common framework. More specifically, using a Bayesian Network is a way of describing any system or entity through a structured probabilistic approach based on both qualitative and quantitative information. It brings the ability to unify various kinds of knowledge into a single representation. On the one hand, qualitative considerations are translated into a specific Directed Acyclic Graph, while, on the other hand, quantitative data mining makes it possible to parameterize and quantify the correlation links making up the network, through a Joint Probability Distribution.

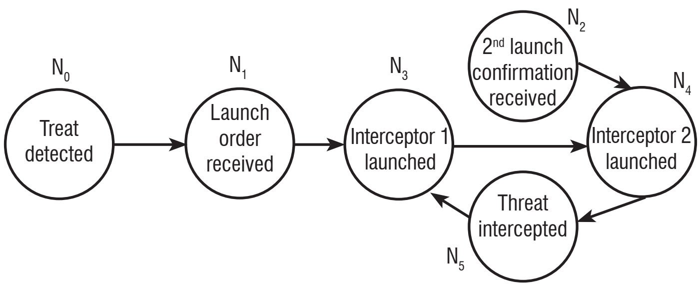


Figure 13 - Example of Bayesian Network used to model a threat interception by two interceptors

Directed Acyclic Graphs (as illustrated in figure 13) consist of nodes and directed arcs. Nodes represent discrete random variables, while the arcs show the causal or statistical interaction between the variables. These diagrams describe a set of conditional independence assumptions corresponding to the graph theoretic notion of d-separation. If two nodes X and Y are d-separated, (i.e., if every path between X and Y is "blocked" by a 3rd variable Z), then X and Y are totally independent, given Z [36] (for example, in figure 13, N_1 and N_5 are independent, given N_3). Whereas two connected nodes have direct causal relationship and one can specify the local conditional probabilities in a Conditional Probability Table (CPT) for each node. For a given node, the CPT aggregates, for each possible state of the variable associated to this node, all of the conditional probabilities with respect to all of the combinations of values of the variables associated to each parent node. Nodes with no parents (N_0, N_2 in figure 13) are called root variables and their CPTs are filled up with marginal "a priori" probabilities.

Under these assumptions, the joint probability distribution P of random variables (X_i) can be factorized as follows:

$$P\left[X_1, X_2, ..., X_n\right] = \prod_{i=1}^{n} P\left[X_i \mid Parent\left(X_i\right)\right].$$

In the case of the BN in figure 13, the joint probability distribution of the random variables X_0, X_1, X_2, X_3, X_4, X_5 is hence given by:

$$\begin{aligned} P\left[X_0, X_1, X_2, X_3, X_4, X_5\right] = & P\left[X_0\right].P\left[X_2\right].P\left[X_1 \mid X_0\right] \\ & .P\left[X_3 \mid X_1\right].P\left[X_4 \mid X_2, X_3\right] \\ & .P\left[X_5 \mid X_3, X_4\right] \end{aligned}$$

The information required to build the network structure and to provide prior probabilities and Conditional Probability Tables can be supplied by expert knowledge or by feedback on the use of the physical system itself. With no observation, the computation is based only on a priori probabilities. Any new observation, called evidence, enhances the accuracy of the system BN description.

Inference algorithms designate the mechanisms used to propagate the probabilistic information throughout the entire network. These consist in computing probabilities for all of the unmeasured nodes, given the information available about the states of the observed nodes (evidence). Algorithms may be sorted into two main families. The first one encompasses the so-called exact inference methods. Ref. [46] and [90] address the Clustering algorithm, which uses the conditional independence properties contained within the network to compute a posteriori exact probabilities. The second one relates to approximate inference algorithms, such as Logic sampling [37], Likelihood weighting [27], Backward sampling [28], Self-importance [91] and Heuristic importance [91]. These algorithms estimate probabilities through multiple draws among the set of possible states for each variable of the network.

Different extensions to BN have been proposed to handle, for example, temporal aspects, logical relations, or the modeling of complex systems.

For a complex system composed of a high number of components or subsystems, the structure of the corresponding BN can be hard to deal with. Object Oriented Bayesian Networks (OOBN) [105] provide a methodological framework to decompose a complex BN into several hierarchical layers. Therefore, a complex system can be more easily modeled by an OOBN from functional analysis and decomposition into physical components.

To model dynamical systems, a temporal dimension can be added to BN, leading to Dynamical Bayesian Networks (DBN) [68] where random variables are indexed by time. Information about the initial state $\left(X_1(0), ..., X_n(0)\right)$ is given through a prior probability $P\left[X_1(0), ..., X_n(0)\right]$. A BN is then used to represent the transition probability by $P\left[X_1(t), ..., X_n(t) \mid X_1(t-1), ..., X_n(t-1)\right]$ defining the temporal probabilistic dependencies between nodes of two time slices. In the particular case of dynamical systems, for which the state evolution can be represented by a discrete time equation, the physical knowledge modeled by this state equation is directly taken into account in the formulation of the conditional probabilities associated to each random variable.

ATLAS method

ATLAS (Analysis by Temporal Logic of Architectures of Systems) is a method developed at Onera aimed at providing a quick macroscopic tool for the probabilistic performance assessment of time-dependent systems.

The most notable frameworks dealing with stochastic approaches for time-dependent systems are generally based on one of the three following approaches [5]: Bayesian networks [48], described in the previous section, stochastic Petri nets [23][70] and fault trees [21][101] or related formalisms [10][98]. Among these approaches, those based on stochastic Petri nets, though interesting, require heavy simulation (combined for example with Monte-Carlo methods). Although the Bayes network approach is interesting, large Bayesian networks reflecting complex systems are difficult to design and maintain. Finally, fault trees consist in a method in which the potential causes of a system hazard are recursively organized into a tree structure reflecting causality - which is a crucial notion in the framework of safety analysis - trying to figure out all of the credible ways in which the hazard may occur.

The ATLAS approach is dual here and does not focus on the reliability of the system, but rather on its performance - although both are of course related. Therefore, one does not consider the sets of causes that lead to a failure, but rather those that lead to a success. This is determined from the functional analysis of the system. Temporal consistency is represented by a modal logic, allowing the expression of time. This can be linked to the fault tree approaches using time propagation such as [35][89] based on the Interval Temporal Logic and the Duration Calculus Interval ([2][110][33][34]).

Contrary to these approaches, the ATLAS method simultaneously combines the time and probability aspects. It was first introduced to evaluate the performance of a defense system [96] and extended to other fields of applications. The detailed method description can be found in [6], [50] and [49]. It was also successfully applied to system analysis in various contexts, such as ballistic missile defense performance assessment [3] and the assessment of space system vulnerability to debris [51].

The determination of the probability of success and necessary delay of a given dynamic system using the ATLAS method is analyzed using the following steps. The system is described as a tree-shaped temporal combination of elementary functions (see figure 14) with a dynamic component.

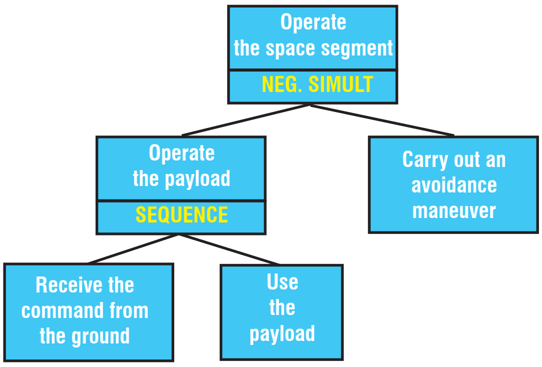


Figure 14 - A tree reflecting the (partial) behavior of a space system

In this tree, the leaves, which are said to be "elementary functions", are distinguished from other functions. They are assumed to be pairwise independent and they represent the input point of ATLAS, in the form of the availability performance defined in the next subsection. The definition of this tree is a key point of ATLAS and must include the two following features: first, the identification of independent elementary functions and, second, temporal links between these functions. The first feature is generally done by functional analysis, the depth of the decomposition depending on the purposes of the study. The second one is generally done using temporal flow diagrams, using a notion of triggering and concluding events, where patterns corresponding to operators are identified (see [49] for further details). How such a tree may be obtained is illustrated in box 3.

In order to take into account the temporal aspect of the performance, the success probability associated with each function is represented as a function of its starting times $(s_i)_{1<i<m}$ and final times $(t_j)_{1\leq i\leq n}$. This representation, called the function availability performance, is illustrated in figure 15 , where the abscissa represents the initial time; the ordinate represents the final time and the applicate represents the probability.

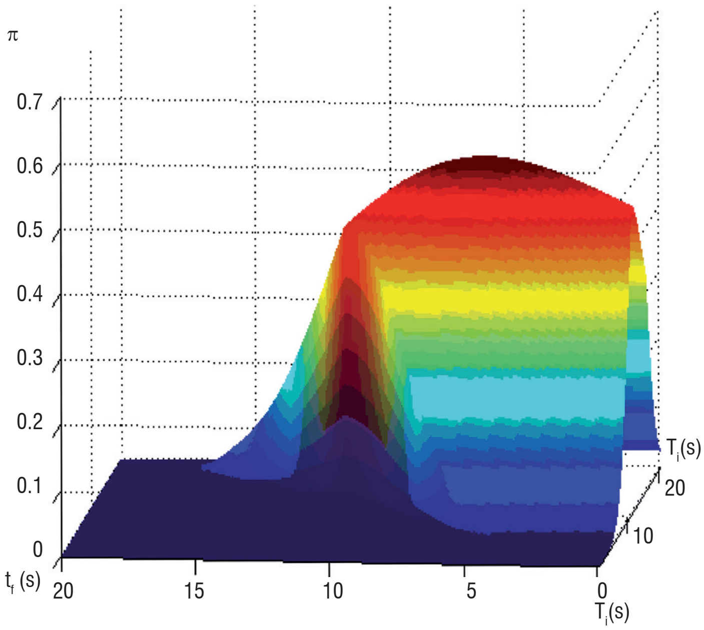


Figure 15 - A function availability performance

Box 3 - Using ATLAS for the assessment of a Ballistic Missile Defense system

Ballistic missile defense (BMD) architecture performance (threat neutralization probability) evaluation is a complex problem. It is therefore of interest to evaluate it without using Monte-Carlo simulations that may prove very costly. The system is described in figure B3-1.

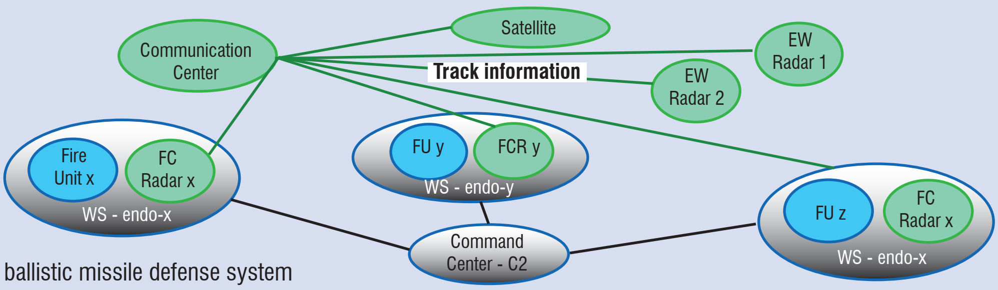
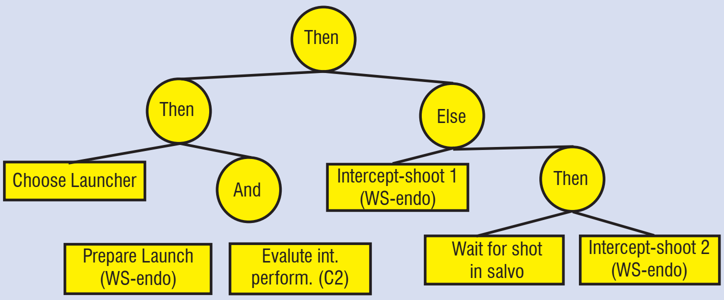
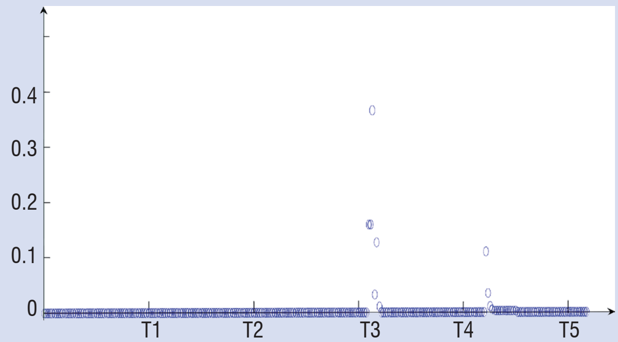


Figure B3 - 1- A ballistic missile defense system

Using the ATLAS methodology, the elementary functions consist, for example, of "Choose launcher" or "Wait for shot in salvo", as presented in figure B3-2 . Elementary temporal probabilities have been provided by experts from the relevant domain.





Since it is a discrete probability of success of the elementary function, this performance notion satisfies: for any s_i, $\Sigma_{1\le j\le n}\pi^{\mathrm{F}}\left(s_i,t_j\right) \le 1$ (as one considers potential failure, this sum may be strictly less than 1). This accumulation represents the overall probability of success of a function F, which could be expressed for all combination of m starting time and n end time by $\Sigma_{1\le i\le m}\Sigma_{1\le j\le n}\pi^{\mathrm{F}}\left(s_i,t_j\right) \;/ m$.

Another way to view this performance is to consider that a service consists in answering an order given at some instant, within a specific answer delay, which leads to the following performance notion: $\pi^F(s,t)$, which represents the probability that function F will provide, at time t, an answer to an order received at time s. In this sense, the performance may be seen as a probability of t being a final time value for each given initial time.

Once the user has defined these characteristics for elementary functions, the purpose of ATLAS is to combine them into a temporal logical way, satisfying the linking constraints expressed by the tree, in order to obtain the availability performance for the full system and the intermediate nodes (see [49] for further details). These performances may be calculated quickly over a large family of scenarios, allowing post-treatments suited to the purposes of the study.

ATLAS is an innovative approach for system assessment, interestingly combining temporal and probabilistic aspects. It has been compared to Monte-Carlo simulations and to dynamic Bayesian networks, and has proved to provide the same results but within a shorter time, since the probability for each pair of starting and finishing times is already set. Its system-engineering-oriented point of view facilitates its use by system specialists and its output for the expected performance at each node of a functional decomposition is also a potentially valuable tool for system design.

New notions are currently considered for use in the ATLAS framework, such as resource consumption evaluation.

Conclusion

In this article, we have presented a large spectrum of methods for evaluating performances of complex systems that could significantly improve the results obtained with classical algorithms. It is nevertheless sometimes difficult to determine a priori which techniques would be the most efficient for a particular case. A major feature is the type of knowledge available on the system behavior. Otherwise, simulation budget, dimension of the problem or density models also play an important role in the selection of the most efficient and suitable methods. Previous analysis of the complex system characteristics must thus be performed before choosing an appropriate approach

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Acronyms

CEP (Circles of Equal Probability)
EGO (Efficient Global Optimization)
PCT (Polynomial Chaos Theory)
POT (Peaks-Over-Threshold)
PDMP (Piecewise Deterministic Markov Processes)
BN (Bayesian Network)
ATLAS (Analysis by Temporal Logic of Architectures of Systems)
CMC (Crude Monte-Carlo)
BMD (Ballistic Missile Defense)

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Simulation of Systems of Systems

Complex systems have become a particular area of interest in the past years and the study of such systems, seen as a whole, has yielded many and varied approaches. One of the difficulties frequently encountered is that such systems display emergence, i.e. their global effect or behavior is greater than the sum of the behaviors of their agents and depends strongly on the interactions between these agents. Simulation is a very interesting approach for this study, since it allows focusing on the dynamic study of the system, thus pointing out these behaviors and interactions. Moreover, it is particularly interesting for aerospace systems, which are nowadays clearly studied as complex systems, since these systems are generally poor candidates for real experimentation, due to many diverse reasons (e.g. cost for space systems, criticality in terms of human life for air transport systems, etc.). Hence, they must be studied quite thoroughly before their full design or realization is possible and simulation plays an important part in this. This paper presents methods that can be used to study complex systems by simulation, as well as some techniques that take into account their specific nature, in particular distributed simulation, a paradigm quite intensively used at Onera. It also deals with the difficulties that may be encountered in setting such large simulations up and also addresses the problem of data in such a large simulation, from the handling to the exploitation.

Introduction

"System" is a very generic term, which is used in all fields of science and may describe practically anything studied: roughly speaking, a system is a collection of elements in interaction, this collection being considered as an object. Systems may be very complicated, but, regardless of that, an orthogonal notion of *complex system* has emerged over the past years. While there is no generally accepted definition of what a complex system is, there are some essential properties that a system needs in order to be considered complex, upon which most authors agree. Mostly, the three main required properties are the following:

- A complex system consists of a significant number of interacting entities (often called *agents*), which can each be considered independently (and may potentially have diverging purposes).
- A complex system exhibits *emergence*, i.e. global behaviors that are greater than the sum of the behaviors of each agent, or at least that are difficult to predict from the knowledge of the individual behaviors of the agents.
- A complex system is not centralized: the emergent behaviors do not result directly from the coordination of a central controller (which does not necessarily exclude the presence of central supervising systems).

Such systems may be found in many various branches of science: biology (e.g. eusocial insect colonies), medicine (e.g. epidemic propagation), engineering (e.g. system design in various fields such as aerospace), chemistry (e.g. molecular self-assembly), sociology (e.g. human networks), computer science (e.g. grid computation), economy (e.g. stock market), etc. Since they encompass very different aspects, they may be studied by various different approaches, which can be roughly divided into two families: static approaches, focusing rather on the properties of the system and dynamic approaches, focusing rather on its behavior.

These dynamic approaches are especially interesting because of the very nature of complex systems, in which the interactions between components make new behaviors emerge. In this regard, simulation is an interesting tool, since it allows data reflecting emerging behaviors to be produced. This data may be used for various purposes, from learning and prediction to the analysis by various methods of the produced data for assessment purposes.

Simulation is an interesting axis for the study of complex systems [7]. It allows both the stochastic and temporal aspects of complex systems to be addressed by developing simulation models, i.e. algorithms or computation codes representing the behavior of a part of the system in response to a defined scenario and putting them together.

Various types of simulation exist and may be used to put a system "in situation" and assess its behavior. However, this simulation approach still sets issues. First, simulations generate large amounts of data that need be exploited, which can be done by various means. Second, since complex systems result from the interactions of various agents, it would seem suitable for the models developed for the simulation of an agent to be able to be reused: this capitalization concept is quite important when studying families of systems (e.g. defense systems). So is the linked question of simulation interoperability: a complex system simulation may be built using the knowledge of various partners and interoperability is the key for such cooperative constructions. Hence, the architecture of the simulation is a very important point.

Simulation may be monolithic or *distributed*. Monolithic simulation, where a single model is developed for the entire system, is easily set up and allows studies on the parameters of the system, or easy running of Monte-Carlo computations over a family of scenarios with slight variations. Distributed simulation is a quite different paradigm, where each individual component of a system is simulated on its own, interactions between these components being modeled as message exchanges between the individual simulators, these exchanges being standardized, or at least complying with a set of common rules. This type of simulation is also sometimes called a functional simulation, because it focuses on the functions[1] of the system. An advantage of distributed simulation is that it allows heterogeneous systems to be taken into account naturally, and facilitates the capitalization of models and the parallel work within a multi-disciplinary team. Moreover, simulation may be set up with the assistance of various techniques, such as the use of a simulation framework or a higher-level description language related to code generation. In addition, various possible points of view may be considered for the use of simulations, depending on the type of study considered: constructive simulation (purely numerical), hybrid simulation (involving hardware in the loop), interactive simulation (with human agents in the loop, mostly for human factor studies or for training simulators).

This paper presents some ideas on how simulation may be used for the study of complex systems. The first section details the various benefits of this approach. In a second section, various tools supporting this simulation approach are presented. In a third section, the issue of simulation exploitation is dealt with. Finally, a fourth section gives some hints regarding possible applications.

Benefits of simulation for the study of complex systems

Interaction and dynamic aspects of a complex system

As has already been pointed out, interaction and dynamic aspects are paramount in the study of complex systems, because of behaviors emerging from these interactions. Hence, dynamic approaches, such as temporal simulation, allow these to be evidenced.

In the aerospace industry, this approach by simulation is particularly needed, one of the main reasons for this being that the considered systems (air transport system, space missions, etc.) generally do not allow real experimentation before a very advanced stage of development. Indeed, this is a consequence of their being, most often, either very critical or tremendously expensive, when not both. Functional simulation is particularly suited in this case: the agents of the system are identified, each of them is separately simulated with the desired (or possible) degree of granularity and the simulation then focuses on the interactions between those agents.

Capitalization and knowledge protection

Even though capitalization aspects appeared very early in the distributed simulation paradigm (concept of "reuse of federates" - federates being a common name for the components of a distributed simulation, which is often considered as a "federation of simulators"), this idea of an "available model catalogue" is in fact just part of the knowledge and know-how that is capitalized upon in using distributed simulation techniques. Indeed, the interaction between models developed by different multidisciplinary teams and their participation in a large scale simulation require an efficient collaboration between the teams designing the various capitalized models.

However, there are in general two possible difficulties in the process leading to capitalization and model reuse, which may be either technical or related to knowledge protection.

Technical problems, typically linked to the fact that models developed independently must be put together, may be solved by offering assistance for model integration, either by using simplifying tools (SIMCORE, Genesis, GAMME - cf. the following sections) or by establishing a close cooperation between integration engineers and modeling engineers (IESTA[2] - cf. the following sections).

Knowledge protection issues can be dealt with, since distributed simulation standards (e.g. HLA, an IEEE standard that will be introduced in a later section) already offer a first level of knowledge protection, since capitalization is done for interoperable "black boxes" and the model remains totally under the responsibility of its initial designer, even though the "black box" must be provided with a clear definition of its possible use, since the link must be established between the design and the use of the models.

This granted, feedback from various projects such as IESTA shows that, as long as providing a model does not mean losing control over its development, capitalization offers a very interesting framework for the participating teams, since it offers an interesting situation of validation and verification of their model, which would not easily be found otherwise.

Therefore, distributed simulation is a good paradigm, even offering a way to concurrent societies to carry out common simulation, by only sharing the necessary interface, protection being ensured by the HLA mechanisms. Moreover, the increasing complexity of systems of systems makes simulation more and more useful and distributed simulation seems unavoidable to ensure a more operational cooperation between teams, e.g. for defense.

Multidisciplinary and model-driven approach

Modeling and Simulation (M&S) technology [26] [27] is an innovative approach for the design and conception of complex systems, which

[1] in the sense of functional analysis

[2] http://www.onera.fr/iesta-en/index.php

appeared in 2000. This framework is aimed at verifying and validating any significant project in simulation as much as possible, before any significant realization (either in terms of cost or criticality). In this context, many simulations are carried out using distributed simulation as a support to construct a multidisciplinary complex system, where the consistency between disciplines is ensured by the integration of the various models into a temporal simulation.

A major interest of the distributed paradigm in this case is that each specialist may have at hand the data needed to describe the evolution of their model and that, since the system is closed, its evolution at time $t-1$ has been taken into account in the acquired data. This approach being valid for all disciplines involved, it is referred to as cosimulation, as described by I. Nakhimovski [24].

Onera has been using these M&S techniques to assess and compare aircraft approach procedures in the first application setting of the IESTA project. This setting was meant to assess the ecological impact of such procedures in terms of noise and chemical pollution around an airport. The multidisciplinary approach involved is illustrated on figure 1.

Important feedback in this regard has been provided by the validation of the IESTA acoustic chain, with measurements from the Aviator campaign. Indeed, the results obtained by the simulation of the conditions of the campaign proved the representativeness of the acoustic model to be good. This validation also needed the other models involved in the simulation, which permitted the flight to be replayed, simulating the reactors.

Simulation frameworks for complex systems

From the problematic stated above, a crucial point emerges for the simulation of systems of systems: time management. In a simulation of a system of systems, it is indeed necessary to maintain (at the system level) a global state divided into subsystems in interactions, all of this depending on time with possibly very different paces. Therefore, it is necessary to have a lean time management, allowing each component to respect its own rhythm, while at the same time keeping a global state as close as possible to the real state.

Distributed simulation does not only bring the benefits of its capacity to make models from various fields of physics (flight mechanics, engine, acoustics, chemical dispersion, etc...- cf. figure 1) interoperable. It also allows the time management issue to be addressed: HLA offers a lean time management relying on various mechanisms allowing a harmonious coexistence of various paces: each system publishes information with a validity period, i.e. a certain time span within which they will not be altered. This way, the system does not need to be studied at the smallest pace of all its components, which would be too demanding.

Moreover, another advantage of distributed simulation is its adaptability with respect to models: it allows these to be integrated by encapsulation, which means that the simulation is fitted to the models, rather than the models fitted to the simulation. This kind of simulation, dealing with models close to those developed by researchers, allows a much easier validation, even though the integration cost is of course higher, since ad hoc encapsulation techniques must be applied for each of the models.

Unfortunately, this approach by distributed simulation is not well disseminated. The main reasons for this are probably the complexity of the standard, which is not easily set up, the important development efforts, and the strong link to support means (COTS) that is required for the exploitation of the simulation [25].

Onera has been investing in the HLA distributed simulation standard for many years and today has a broad range of proficiency and tools for setting up such simulations easily (cf. the following sections).

Simulation exploitation

Considering the very large scale of industrial simulations (which in an aerospace context typically may include a whole day of traffic around an airport, the study of a satellite constellation over its lifetime of 15-20 years, etc.), the amount of data produced by any of these is tremendous and may not be treated by a human operator; hence the need for assistance analysis tools. This amount of data is actually

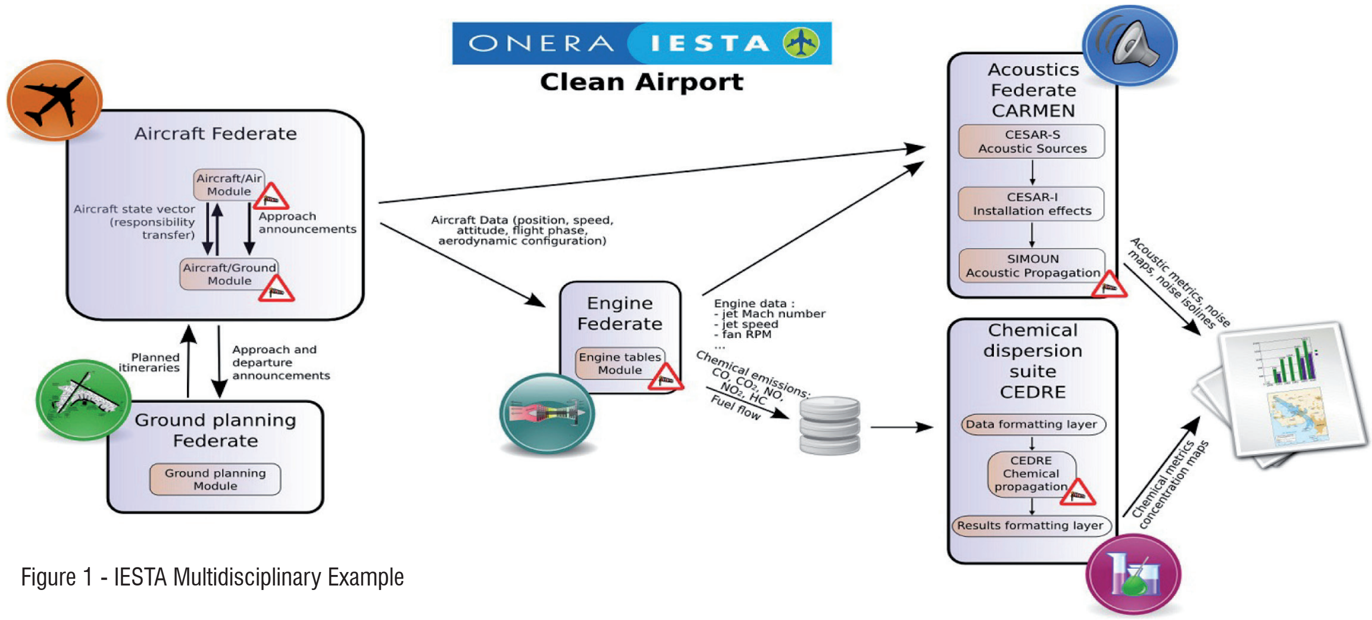

Figure 1 - IESTA Multidisciplinary Example

sometimes so huge that it may not even be saved for future treatment and must be analyzed online, which is impossible without some automated assistance.

This section presents one example of techniques that may be used for this purpose: chronicles, a formalism focusing on the description and recognition of behaviors. Chronicles rely upon the idea that the events generated by the simulation contain enough information on the behaviors occurring within the simulation to be directly exploited by identifying behavior signatures within their time-ordered succession. These signatures are expressed by logical expressions called chronicles.

Chronicles

For this purpose, a temporal approach is naturally particularly suited and temporal logic is a very powerful tool for the analysis of the behavior of large systems of systems. It may be used in order to make macroscopic assessments on the global behavior of a system, as in [6] [21] [23], but this last approach is a global one, not particularly suited for distributed simulation.

A very interesting approach focuses on following a simulation for the instantaneous, certain detection of behaviors throughout time, rather than on the global assessment of the likeliness of a behavior, providing an expression power and the possibility of detecting behaviors through the observation of their characteristic traces. This technique is not only useful for the exploitation of simulation, but also potentially for their development (cf. e.g. [10])The characteristic traces are expressed through correlations of interactions (called events) in the system and these correlations are represented using a formalism called chronicles for their fine detection. This formalism was introduced by Dousson et al [14] and developed by Carle and Ornato [8] and Dousson et al [13] [15] [16].

In this approach, events cannot occur simultaneously and durations are not associated with events, thus considered as instantaneous, but time may indeed be taken into account using special events corresponding to clock ticks. A chronicle describes relationships between the events of a sequence ordered with respect to time. The goal is to identify all instances of the chronicle schema within an observed event flow (where events are ordered).

Chronicle identification is achieved through the matching between events of the flow and events in the chronicle description, while flow events that do not contribute to the chronicle recognition are simply ignored. In addition, it may be of interest to save the piece of information stating which events in the flow contributed to the chronicle recognition, because it may help to find the causes of the observed events. A first modeling of chronicle recognition and its application to the analysis of distributed simulation was proposed in [1] [2] [3] [4] and a reworked version of the previous work in [9] [22].

Simulation Tools

The previous section gave some flavor of the kind of techniques that can be used for distributed simulation; here, some actual techniques will be presented, focusing around the High Level Architecture (HLA), which has been the NATO recommended standard for distributed simulation since as early as 1998[3] . HLA has been used also in other non-military contexts, for instance, to design civilian air traffic simulations. This section first describes the HLA standard. Then, it presents three Onera tools that were developed to assist distributed simulation designers and make the development of such simulations go more easily and smoothly: the first one, CERTI, is an HLA implementation; the second one Genesis, relies on a description language allowing to automate and make consistent as much as possible from the development process of a simulation; the third one, SimCore, consists in a framework providing a generic model integration process. Finally, another approach for the development of distributed simulation is presented, the originality of which is that it is data-centered and may be used to generate models complying with various standards or tools, including HLA.

HLA

A very popular standard for distributed simulation is the IEEE High Level Architecture [17] (abbreviated HLA). Its principles were originally developed by the United States department of defense [12], but quickly spread to industry and finally led to an IEEE standard, in which the simulation consists in various components - called federates - which are linked in a federation, in which communications and interactions take place [18], regardless of the characteristics of the computing platform.

A High Level Architecture model consists of:

- an object oriented interface specification, describing how the platform will interact with the communication manager soft ware: the Run-Time Infrastructure;
- an object model template (OMT) [19], defining how information is shared between the various agents composing the federation;
- a set of rules ensuring compliance with the HLA standard.

Box 1 presents an example of a run-time infrastructure: Onera's CERTI.

The object model template is composed of documents describing the federation at various levels. The Federation Object Model describes the interactions and attributes of the entire federation. It is composed of all of the Simulation Object Models, which describe the same features for every single federate. Each Simulation Object Model is unique and evolves together with one federate of the simulation, while the Federation Object Model is common to the entire federation and must be updated every time a new component, requiring new interactions, is added to the federation.

[3] "The High Level Architecture (HLA) is the preferred Simulation Interoperability Standard recognized by NATO as early as 1998", quoted from NATO Modelling and Simulation Group (NMSG): http://www.rto.nato.int/panel.asp?panel=5

Box 1 - CERTI

CERTI is an HLA RTI developed since 1996 by Onera, the French Aerospace Lab.

The initial purpose of CERTI was to develop a homemade RTI in order to: learn HLA usage and HLA RTI internals (e.g. time management) and have total control over source code in order to use this particular RTI with specific modifications in several research projects (security mechanism, multi-resolution, high performance distributed simulation, etc.).

CERTI became open source[5] in 2002. Since then, the Open Source CERTI project has been mostly driven by research project needs and funds. CERTI is drawing increasing interest from the HLA

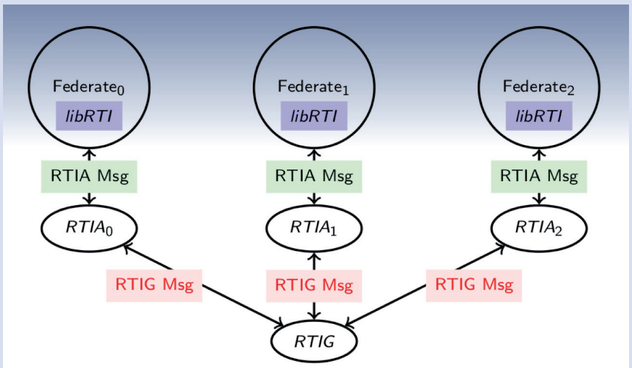

Figure B1-01 - CERTI messaging architecture

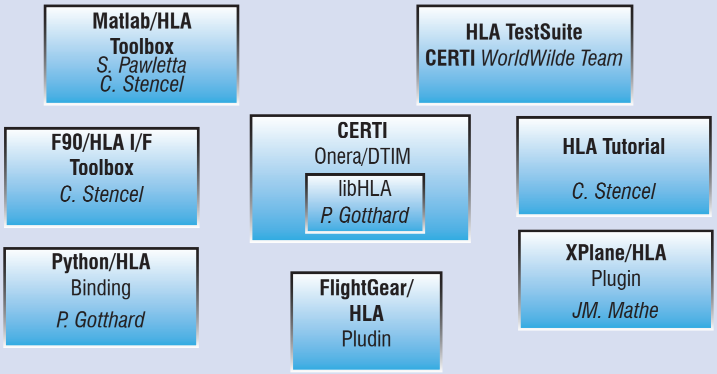

Figure B1-02 - Components of the CERTI

CERTI has a classical communicating process architecture depicted in figure B1-01, making it very portable on various operating systems. CERTI currently works on various Unix platforms, including Linux and various Windows OS flavors. CERTI is natively written in C++ but offers binding in Java and Python.

The CERTI messaging infrastructure makes it generic, a message-oriented middleware. Every HLA service is implemented using a predetermined set of message exchanges between Federates, its RTIA, and RTIG.
The RTI Gateway (RTIG) is a centralization point in the architecture. Its function has been to simplify the implementation of some services. It manages the creation and destruction of federation executions and the publication/subscription of data. It plays a key role in message broadcasting, which has been implemented by an emulated multicast approach. When a message is received from a given RTIA, the RTIG delivers it to the interested RTIAs, avoiding a true broadcasting [see: CERTI messaging architecture]

A specific role of the RTIA is to immediately fulfill some federate requests, while other requests require messages with the RTIG. The RTIA manages memory allocation for the message FIFOs and always listens to both the federate and the RTIG. It is never blocked, because the required computation time is reduced. It also plays a great role in the implementation of the Time Management HLA Service.

HLA is a DoD defined simulation standard, which is now the IEEE-1516 standard. It is publish/subscribe oriented middleware that could be compared with OMG DDS. However, HLA has a unique feature, which is Time Management service. The Time Management service makes it possible for each simulation stakeholder (called a Federate in HLA wording) to ensure that all of the data or events that it receives or sends are causally ordered. CERTI makes no exception to this and implements the HLA time management service using the well-known Chandy-Misra-Bryant NULL message conservative algorithm. CERTI even has a unique feature, which is a modification of this protocol to greatly enhance the protocol performance in some event-driven situation: this is the NULL message PRIME conservative algorithm.

More than a simple HLA compliant RTI implementation, CERTI is an ever growing Open Source community that contributes original software within or around CERTI as depicted in figure B1-02. CERTI is currently evolving towards the HLA 1516 standard [17].

[5] components of the CERTI

Genesis

HLA is a very powerful technology, but may be rather heavy, especially because of some redundancies in its development process. To simplify this part of the work, a tool, Genesis [5], has been developed by Onera to simplify most of these redundant parts and is helpful both to the developers and the specifiers. Genesis consists in a language, in which a high-level description of an HLA simulation component or a whole HLA federated simulation may be specified, and an engine, processing such specifications in order to generate the source code for the components, along with the documentation required by the standard and the configuration files, ensuring that they will be able to interact properly with each other in the federation. Figure 2 displays the principles of Genesis.

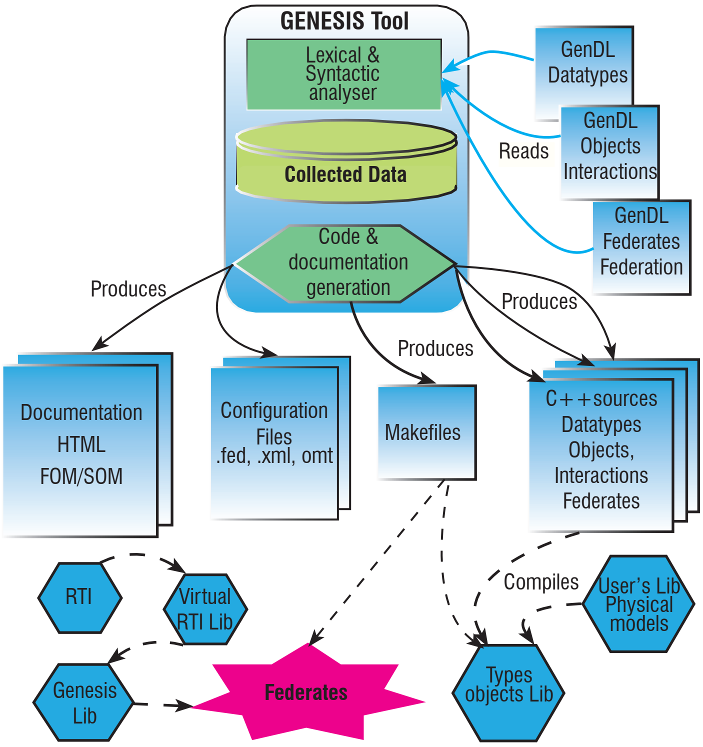

Figure 2 - Principles of Genesis

Its main purpose is helping the developer in all automatable phases of the writing of an HLA component, i.e. the consistency between the object model and the federate software and the handling of existing federates, object models and federations, and this during the whole development process, from the description until the production of fully functional federates, without additional work. Besides, Genesis is also an engineering tool, allowing the generation of project-related files, in order to facilitate the development process and offering developers a support and dedicated tools from the design and specification process to the testing process.

Simulation Framework Approach

The need for a framework

Since system of systems simulations involve more complex operational scenarios, simulation engineers face very challenging requirements, so as not to lag behind.

To cope with these increasing expectations, a global approach needs to be undertaken to find the most generic solution. A "framework" provides an extensible and flexible structure, to ease both the development and the exploitation of new applications. It covers a large spectrum of system of systems applications; it also supports engineers across the entire simulation process: developing new simulations, preparing complex scenarios on a map, executing and controlling their simulation, using 3D visualization and processing the results.

The framework composition and services

A framework is made of a set of coherent components, which are listed hereunder:

- a simulation engine

The framework relies on a simulation engine that serves as a core for model integration and tool development. Its applications may concern both civilian and military domains. Within this engine, our simulation entities (aircrafts, ground vehicles, etc.) are considered as actors. Actors exhibit attributes, which have a type, a value and systematic getter/setter functions. They communicate within a simulation through messages. A manager directs the actors and is responsible for the entire simulation process (including time management and scenario loading). A set of common core services is also available for models: it concerns mathematic functions, input/output handling and geographic services (numeric terrain model, atmosphere and ephemeris model, etc.).

- a library of capitalized models and actors

The engine comes with a standard library of capitalized actors and models. For defense applications, this library (provided by MEFISTO) involves models for sensors, weapons, platform mobility, artificial intelligence, tactical data links, battle damage and decision processes. All platform actors publish kinematic attributes in a standard way, know how to take damage from different kinds of weapons, understand damage states, can perform dead reckoning for both local and remote vehicles, and have the infra-red and radar cross-section attributes useful for sensor models

- a set of exploitation tools

Scenario preparation: in this phase, the different actors of the simulation (platforms, sensors, weapons) are defined, together with their technological parameters, their force affiliation and their initial behavior. The GIS capabilities of the tool help us to precisely locate the actors in the world. At the end, the scenario is saved in XML format. The scenario editor relies on the generic concepts of the underlying engine; nevertheless it is possible to customize it for a particular application, thanks to a plug-in architecture.

Simulation execution and control: the execution mode depends on the user context. It is both agile and scalable. It is agile because we can choose between three modes: a batch mode with no GUI (for development and automatic tests), an execution mode from a stand-alone tool called Scenario Manager (for fast simulations and visual checking) and a full deployment mode on a HLA federation (for demonstration purposes, performance optimization and interoperability). It is scalable because, in HLA mode, each federate can be parameterized with a list of actors to physically simulate. The simulation can also be visualized in three dimensions thanks to a Stealth Viewer.

Result processing: The framework provides result processing and analysis tools: chart visualization of simulation results, easy trajectory replay from Scenario Manager, and federation execution replay from the Stealth Viewer.

The framework status and perspectives

The current version of the framework was developed by an in-house research project called AMAO [11]. The purpose of this project was to study the role and the concepts of Unmanned Aerial Vehicles (UAVs) in future offensive missions. The resulting experimentations can use both constructive and virtual simulations to assess various issues, such as the role of the different actors in the decision making process, the overall mission timing and coordination process, the efficiency of subsystems (sensors, weapons) and algorithms (image processing and data fusion) and the robustness of the proposed system concepts.

The current MEFISTO research project is aimed at extending the framework with new models to perform new applications. Since the framework turned out to be an agile and generic backbone, we would like to keep on capitalizing models for new scenarios, filling the needs of future Onera projects.

GAMME & SIMSKY

When designing distributed simulation systems, data management is a particularly crucial issue. Data management is about storage, access, distribution and representation of entities that are shared by different simulators. The approach presented here puts data management at the core of the simulation development process.

We distinguish between two kinds of data: persistent and non-persistent (transient). We could also say static and dynamic data. Persistent data is used to initialize the simulation. It may be stored in a relational database or some files, like XML files. Access to it can be obtained by querying the database or reading the files. Transient data is about dynamic data evolving during the simulation. For example, an airplane will be initialized with static data (number of passengers, initial mass, etc.) and its dynamic behavior will be described by a state vector (position, speed, current mass, etc.). Dynamic data is not stored, but distributed between the different components of a simulation, e.g. an aircraft simulator will publish state vectors, whereas an ATC radar simulator will subscribe to them to display radar tracks.

All of this data may have different representations, especially in heterogeneous simulations where simulators are developed in different languages. An entity may be represented by some tables in a relational database, classes in object-oriented programming languages, some textual or binary file formats, etc. Consistency must be ensured between these different representations, but maintaining them may become very repetitive, painful and error-prone.

This is why Onera has developed GAMME, a tool aimed at deriving many different representations starting from a single “unified” data model. It consists of a conceptual data editor and transformation mechanisms. GAMME relies on the Model-Driven Engineering (MDE) methodology. The users define domain-specific data models, that is, abstract representations of the knowledge shared by the different components of a simulation, and apply transformations on them. Transformations result in pieces of code, database schemes, XML schemas, etc., which are then used by simulator developers to access or distribute data. Thus, developers can concentrate on their domain-specific code (physics or mathematics) and not on IT-related code, for instance, focus on how an aircraft flies and not on how aircraft data is stored or shared with other simulators. This approach is meant to offer a common design, independent from the target representations, and to increase productivity by reusing transformations and generating huge and errorless code.

The first application of GAMME to distributed simulation is the SimSky project.

SimSky is the second version of the IESTA platform. It is aimed at assessing innovating concepts in the ATM system of systems: for example, Onera is currently involved in projects studying fully automated air transport systems, the impact of introducing drones in general aviation airspace, a concept of personal air transport, etc. Such studies are based on refining concepts increasingly through validation steps which rely on iterative simulation.

In this perspective, Onera needs a tool for rapid and iterative prototyping of ATM concepts. Many distributed simulation platforms already exist, however they do not fulfill all SimSky requirements, for instance because of lack of flexibility, complex programming interfaces, proprietary code, limited number of programming languages, etc. Conversely, SimSky aims at proposing a number of facilities:

- a domain-specific data modeling thanks to a user-friendly GUI, promoting iterative prototyping of concepts,
- the rapid interconnection of multi-disciplinary models (e.g. flight mechanics, conflict detection and resolution, strategic planning, etc.) through distributed simulation and simple APIs,
- an open infrastructure, available on several operating systems and programming languages dedicated to various needs and programmer skills: scientific computation (like Matlab/Fortran), algorithmic (CAML), performance (C/C++), GUI (Java), rapid development (Python), etc.,
- tools for the supervision and monitoring of simulations, like air traffic visualization,
- a set of default simulation models (air traffic simulation, weather model) allowing algorithms to be quickly tested in an ATM simulated environment,
- fast-time and real-time / manned and unmanned simulation capabilities.

All of the IT-related code is automatically generated with GAMME: database access, file management, data distribution over the network through middleware, such as the rapid prototyping-oriented Ivy[4], or the reliable and interoperable HLA.

We now present some actual and representative applications of distributed simulation in which Onera is involved: the first is set up in civilian air traffic context, whereas the second deals with a framework for the testing of defense concepts.

Applications

ASTRAL & 4DCoGC

One of the first applications using SimSky will be ASTRAL. This research project is aimed at deeply studying the concepts introduced in the European Project 4DCoGC.

[4] http://www.tls.cena.fr/products/ivy/

These projects study a revolutionary post-SESAR concept for a future ATS (Air Transportation System) by adding as much onboard autonomy to the aircraft as necessary to fulfill the overall requirements of improved efficiency and safety of air transportation.

The system of systems studied by both ASTRAL and 4DCo-GC is composed of Airline Operation Centers, a centralized ground-based ATSM (Air Transport System Manager), aircraft, data-link communication systems, etc. The ATSM and aircraft are themselves systems, some parts of which can be individually simulated (for example, FMS, auto-throttle & auto-pilot, local aircraft re-planning system). Such a system is illustrated in figure 3.

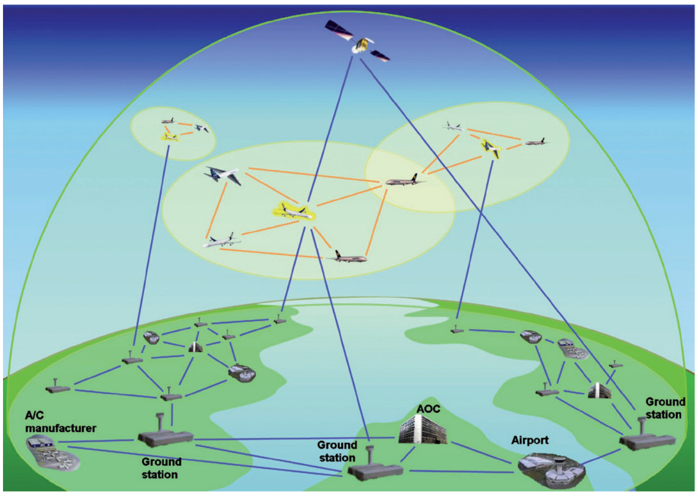

Figure 3 - An ATM system of systems

The central idea of "4D-contract" is that each aircraft must be at the right place at the right time and implies that the aircraft is fully responsible for following the 4D-contract that has been assigned to it by the ATSM. If the aircraft finds that it cannot comply with the contract (due to unpredictable weather conditions or unexpected events, such as a runway closure), then it re-negotiates a new contract with the system. Margins around the expected positions are represented by "freedom bubbles", where the aircraft can move without having to re-negotiate and "security bubbles" to ensure aircraft separation.

The main objectives of ASTRAL are to define and implement models and algorithms for 4D planning and 4D-contracts guidance and monitoring, put the concept under stress via iterative simulations, then present results about the concept's robustness towards the input parameters of planning algorithms (take-off weight, weather, etc.) and finally draw lessons from this to make recommendations on freedom and security bubbles.

MEFISTO

The MEFISTO research project objective is to provide a battlelab for the French Aerospace Lab. This battlelab relies on a simulation framework filled with a library of capitalized Onera models. It focuses heavily on interoperability, and will be connected to the French Army laboratory for technical and operational simulation (DGA LTO) through a dedicated collaboration network (EXAC and the ITCS gateway). Thus, it will authorize collaborative simulations and experimentations with DGA and the other connected battlelabs (e.g. of major industry groups like EADS, Thales, MBDA, etc.).

The main achievements of MEFISTO are:

- the development of two applications :
  - PANTHERE dealing with the study of missile penetration in air defense assets,
  - SITAC dealing with tactical situation awareness on the battle field;
- an interoperability experimentation with the DGA: an independent unmanned air vehicle strike mission will be simulated, part of the models being carried out by the DGA LTO in Arcueil and the other part by the Onera in Palaiseau.

Conclusion

Simulation is a very important approach for the study of complex systems. Especially in the case of aerospace systems, which cannot be directly tested because of their cost or criticality, simulation is a perennial, indispensable activity for designing and testing new concepts.
As this paper shows, simulation of complex systems goes far beyond the simple virtual restitution of a complex system. It takes into account multidisciplinary aspects and also secondary purposes such as capitalization, knowledge protection, easy prototyping, and mutualization, which do not only allow simulations to be set up, but also go beyond the study of the systems to focus on their interactions and allow the consequences of the use of system concepts to be tested.
Onera has a broad panel of tools for the simulation of complex system and the exploitation of the data produced by such simulations, thus positioning itself for the study of future techniques or system designs. These simulation techniques are a new and innovative means to design, test and even validate complex system concepts. It also offers access to a larger audience to the possible consequences of such new concepts, since they allow the system to be viewed in its environment and also provide a way to show these results to the research teams involved in the development of a simulation.
As for exploitation techniques, which are paramount in the simulation approach, they constitute a very active field of study, as has being outlined in this paper. Some interesting perspectives to this extent can be seen in the use of description languages (e.g. the NAF — NATO Architecture Framework) in order to specify the complex system in such a way that the difficult points to be particularly considered in the simulation will be outlined ■

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Acronyms

4DCoGC (4-Dimensional Contract Guidance and Control of the aircraft)
AMAO (Autonomie des Missions Aéroportées Offensives - Onera federative project on the autonomy of offensive air missions)
ASTRAL (Automatisation des Systèmes de TRansport Aérien à Long terme - long-term air transport system automation)
ATC (Air Traffic Control)
ATM (Air Traffic Management)
ATS (Air Transport System)
ATSM (Air Transport System Manager)
CERTI (Onera's RTI)
DGA (Délégation Générale pour l'Armement - Division of the French Defense Ministry)
EXAC (EXpérimentation pour l'Acquision de Capacité - DGA secure network for experiments)

FOM (Federation Object Model)
GAMME (Génération Automatique pour la Métamodélisation Métier Enrichie - Onera project on metamodelling and data-centered techniques for code generation)
GENESIS (Onera's assistance tool for the generation of HLA-compliant simulations)
GIS (Geographic Information System)
GIS (Graphical User Interface)
HLA (High-Level Architecture)
IEEE (Institute of Electrical and Electronics Engineers)
IESTA (Infrastructure d'Évaluation des Systèmes de Transport Aérien - Onera infrastructure for the evaluation of air transport systems)
ITCS (Infrastructure Technique Commune dédiée à la Simulation pour l'acquisition - Technical M&S infrastructure for supporting SBA process)
LTO (Laboratoire Technico-Opérationnel - technical and operational laboratory)
M&S (Modeling & Simulation)
MEFISTO (Moyens d'Études Fédérés et Interopérables pour la Simulation Technico-Opérationnelle - Onera federative project for the study of technical and operational simulation)
NATO (North Atlantic Treaty Alliance)
OMT (Object Model Template)
RTI (Run-Time Infrastructure)
RTIA (Run-Time Infrastructure Ambassador)
RTIG (Run-Time Infrastructure Gateway)
SBA (Simulation-Based Acquisition)
SESAR (Single European Sky ATM Research)
SimCore (Simulation Core)
SimSky (Onera's fast-prototyping simulation architecture)
SOM (Simulator Object Model)
XML (EXtended Markup Language)

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