Mastering Complexity: an Overview

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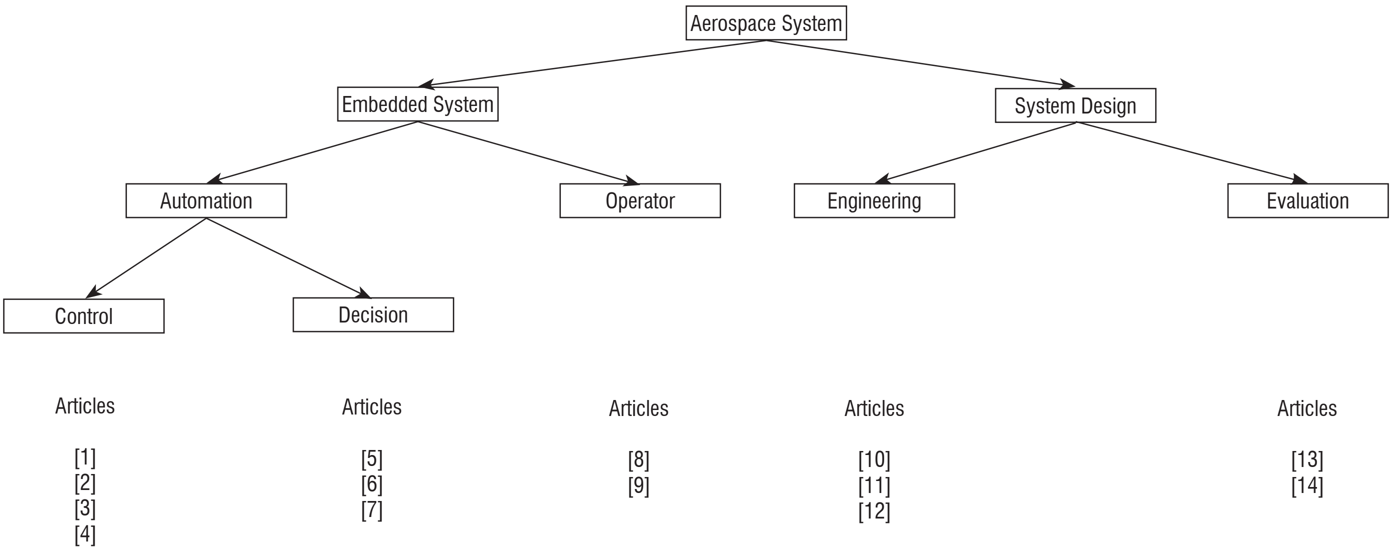
Aerospace systems are certainly part of those of which the complexity has been dramatically and continuously increasing for several decades. Not only are the vehicles increasingly more sophisticated but, since they are interacting increasingly with other so-called "intelligent" systems, human or machines,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