Rotary Wing UAV pre-sizing : Past and Present Methodological Approaches at Onera

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Thanks to their Vertical Take-Off and Landing, hover and low speed capabilities rotorcraft have a wide variety of applications. A very wide range of rotorcraft concepts have been invented and creativity is still abundantly present, especially in the field of Rotary Wing Uninhabited Aerial Vehicles. First, some typical past studies requiring RW-UAV pre-sizing will be described. They were pragmatically dealt with using the means available at that time. The interest as well as the limits of these studies contributed to pushing Onera in the development of a dedicated tool for rotorcraft evaluation and pre-sizing with the most ad hoc models and methods. The second part of the paper will present the main lines of the current methodological approach built in the CREATION project: “Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network”. Then, some evolution perspectives of this numerical platform will be given, to better address especially the RW-UAVs pre-sizing.

Introduction

An Uninhabited or unmanned Aircraft System (UAS) is composed of four main components: the air vehicle (called UAV hereafter), the payload, the control station and the data link. The operators interact with the UAS through the data link and are usually located in the control station. The focus of this paper is on the vehicle itself (UAV) and more precisely on rotorcraft, a widespread category of air vehicles.

Indeed, rotary wing aircraft have a very wide range of applications, thanks to their Vertical Take-Off and Landing (VTOL), hover and low speed capabilities. In addition, since they do not require a runway or any heavy facilities, they are more often used than fixed wing aircraft for research in aerial robotics by universities and research institutes. Therefore, a very wide variety of rotorcraft concepts have been invented. This creativity has been reinforced by the blossoming and rapid expansion of UAS projects, due to their reduced cost and risk of development, compared with inhabited aircraft. This paper is dedicated to Rotary Wing Uninhabited Aerial Vehicles (RW-UAV).

Without claiming to present an exhaustive review of all rotorcraft concepts here, a brief overview of the main categories can however be given.

Five main categories of rotorcraft can be distinguished :

1. "Tilt Blade Tip-Path-Plane": this is the most widespread case, the most well-known rotorcraft being the helicopter, with a main rotor used both for lift, propulsion and the pitch and roll controls. The blade TPP is tilted by using cyclic controls, changing the lift distribution over the rotor disc, causing different blade flapping angles.
2. "Tilt-Body": in this case, different rotors are used and the total aerodynamic force resulting from their thrust can be tilted by inclining the whole aircraft or the part on which the rotors are fixed.
3. "Tilt-Rotor": one or more rotors are tilted entirely, i.e., their shaft is directly oriented in the direction in which the main force must be produced. This can be : one TR like in the Rotoprop case, where the tail rotor is used in hover and low speeds like a classical anti-torque rotor and at higher speeds like a pusher rotor, or two tiltable coaxial contra-rotating rotors like in the Verticopter concept or more TR, etc.
4. Different Lift / Propulsion devices: in these cases, rotors are combined with wings, propellers or other auxiliary propulsion. The rotors are mainly used for producing lift at low speeds; this lifting function is partially or totally completed by wings at higher speeds.
5. Special cases are when the rotor itself becomes fixed wings, for instance by stopping it at high speeds (case of stoppable rotor) or by retracting the blades in a circular wing, in the case of the variable diameter rotor.

Given the large variety of rotorcraft concepts, selecting the best suited concept for a certain type of application is often not straightforward. Indeed, even though some concepts are better suited for high speed flight and others for low speed flight for example, this kind of flight performance criteria must be supplemented by many others for a correct concept selection, including flight safety, cost, maintainability, environmental impact, etc.

Beyond this first difficult step of concept selection, another difficulty is the pre-sizing of the various design parameters typical of a certain rotorcraft concept: number of rotors, number of blades, radius, mean chord, rotational speed, etc. Hence, the design engineer has to cope

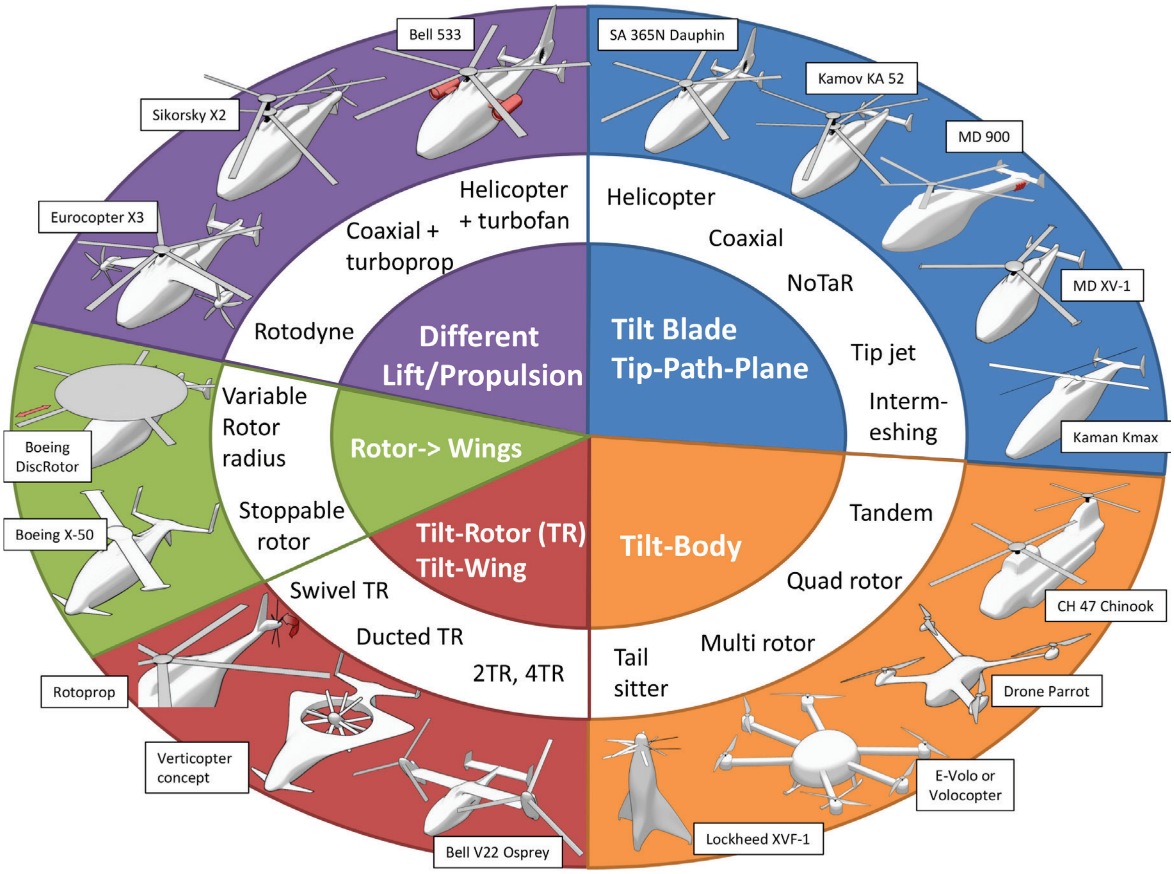


Figure 1 - Overview of the different types of rotorcraft concepts

with a multivariable multi-objective optimization problem under constraints (design rules, operational constraints, airworthiness regulation, etc.).

As indicated from the title, the paper is dedicated to the presentation of the evolution of Onera approaches in this field. Of course, it would have been interesting to include a description of the methods developed elsewhere, but the extent of the paper does not allow such a wide presentation.

First, some typical past studies requiring RW-UAV pre-sizing will be described. They were pragmatically dealt with using the means available at that time. The interest as well as the limits of these studies contributed to pushing Onera in the development of a dedicated tool for rotorcraft evaluation and pre-sizing, with the most ad hoc models and methods. The second part of the paper will present the main lines of this methodological approach built in the CREATION project: “Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network”. Then, some perspectives of the evolution of this numerical platform will be given to better address especially the RW-UAV pre-sizing.

Past : earlier studies about RW-UAV pre-sizing at Onera

Three examples of past studies dealing with RW-UAV pre-sizing will be briefly presented hereafter: two concern European projects (CAPECON and MAVDEM); the third is an expert assessment performed by Onera for the French government (ExDro).

CAPECON

CAPECON, which stands for “Civil UAV APplications & Economic Effectivity of Potential CONfiguration solutions”, is a European project of the 5th framework, involving 20 organizations (9 industries, 5 aeronautics and space institutions and 6 universities) from eight countries. The project was mainly developed from 2001 to 2005, with three groups working in parallel: two working on fixed wings (one on the High Altitude Long Endurance concept (HALE-UAV) and the other on Medium Altitude Long Endurance (MALE-UAV)) and the third one working on RW-UAVs.

From a survey of potential civil RW-UAV applications, five different application groups that were similar in terms of requirements were defined, taking into account the range, endurance, altitude, payload, speed, safety, all weather capability, etc. An analytical study was performed based on a multi-criteria matrix method resulting in the selection of the two most promising multi-role missions: one for In-Line of Sight missions (local missions) and the other for Out-of-Line of Sight missions (broader range missions). Hence, two operational concepts were derived defining their respective specifications in terms of payload, flight performance and other mission requirements.

At that time, there was no tool (models and methods) for selecting the most suited rotorcraft concepts. Therefore, the choice was done following a rather conservative approach, allowing the use of the available pre-sizing means for a conventional single main rotor / single tail rotor helicopter on the industry side. However another “less classical” configuration was studied : a coaxial rotorcraft with two contra rotating coaxial rotors (see figure 2).

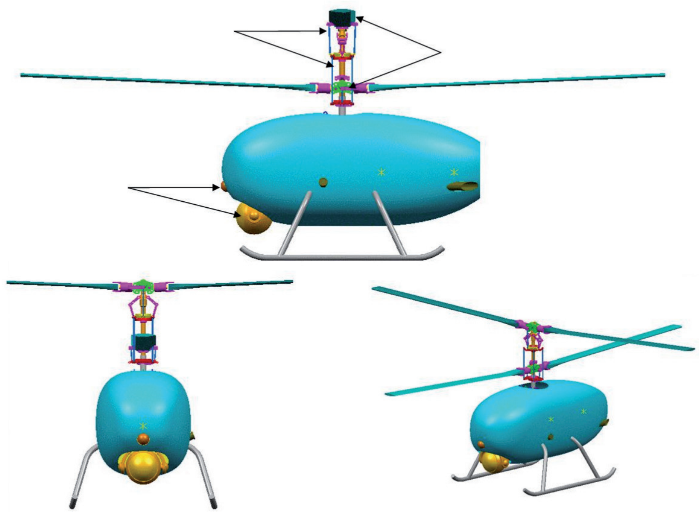


Figure 2 - CAPECON coaxial RW-UAV (from [1])

As described in [1], Eurocopter adapted its empty weight calculation model by adjusting the sizing laws and technological coefficients based on a database collected from existing RW-UAVs available at that time. This adaptation was of course needed to take into account the smaller sizes and thus lighter weights of UAVs compared with inhabited helicopters. The engine plays a significant role in both the weight breakdown and the flight performance. The choice of engine type (electrical, piston or turbine engine) depends primordially on the power demand. In the CAPECON case, the payload weighed 150 kg and the Maximum Take-Off Weight was of about 500 kg. Therefore, a piston engine was selected. A statistical engine model was derived from an aeronautical piston engine database for estimating its weight and performance in terms of available power and fuel consumption versus temperature and altitude.

The flight performance in terms of ceilings, range, endurance and speeds result from the balance between the power required by the rotors in steady flight conditions and the useful power provided by the engine (taking into account the mechanical losses and other power consumption by the equipment). Thus, the required power is a key parameter. For the coaxial configuration, Eurocopter applied its tool built for single main rotor helicopters and then tuned some empirical modeling parameters based on a bibliographical study of coaxial rotorcraft.

Among different contributions to the rotary wing group of the CAPECON project, Onera developed an inflow model for coaxial rotors, in order to better assess the flight performance of this configuration. Indeed, the induced power required by the rotors to produce the lifting force is the most important term in the power demand, especially at low speeds. Moreover, one of the most important specificities of the coaxial configuration (with respect to the single main rotor helicopter) is the aerodynamic interaction between the two rotors. Therefore, a model was created for calculating the mean induced velocity through each rotor in interaction with each other. The model is applicable in hover, vertical climb or descent flight, as well as in forward flight. It takes into account the radial contraction downstream in the rotor wakes, as well as the fact that in forward flight the rotor wakes are skewed backwards, reducing the aerodynamic interaction. Above a certain forward speed, there are no more rotor interferences and the required power is then closed to the case of two isolated rotors. This coaxial rotor inflow model is described in more detail in [2].

This model was later improved and adapted for another RW-UAV, dedicated to the inspection of large structures, such as dams, bridges, dykes, cooling towers, factory chimneys, or cliffs, etc. A flight dynamics model was built by Onera for the Infotron coaxial UAV, within the context of the ADOPIC project *("Aide au Diagnostic d'Ouvrages Par Imagerie Conventionnelle")*.

Figure 3 - IT180-5, coaxial UAV (Infotron)

In this paper [2], three levels of analysis for assessing the RW-UAV steady flight performance have been presented :

- analytical calculation by the energy method ;
- flight mechanics computation, taking into account the comprehensive equilibrium of forces and moments resulting at the rotorcraft center of gravity ;
- overall performance assessment, in terms of the power required and fuel consumption on a complete mission profile, including: hover, climb, cruise, descent, loitering flight, etc.

Here, only the analytical calculation of the required power is recalled and discussed as an illustration of that previous work. At the level of the power balance or energy method, the CAPECON coaxial configuration was compared by Onera with equivalent ones: the helicopter, tandem twin-rotor and tilt-rotor concepts. Here, equivalent means comparable. The equivalent helicopter has a single main rotor with four blades instead of two rotors with two blades. The tandem has two rotors exactly identical to those of the coaxial configuration, but separated. The tilt-rotor concept has two smaller rotors, but with three blades whose dimensions (radius and mean chord) are calculated in such a way that the rotor solidity is the same as in the other configurations. Thus, all the four configurations have the same rotor solidity (ratio between the surface of blades and the rotor disc surface).

An example of a comparison between these four configurations is shown in figure 4, where the power required versus the forward speed is plotted from a hover flight to straight and steady level flights up to 280 km/h. At low speeds, the tandem required less power than the others thanks to its two large separated rotors, the worst case being that of the tilt-rotor due to its two smaller rotors demanding more induced power and producing a downwash on the wings. At higher speeds, the trends are inverted: the tilt-rotor requires less power and can go faster in its airplane mode, whereas the tandem is hindered by the drag penalty, due to its longer fuselage and larger pylons (parts between the fuselage and the rotor heads). The helicopter and coaxial configurations are good compromises. The coaxial configuration is better at low speeds and more significantly at intermediate speeds where the required power becomes very close to that of the tandem case when the two rotors have negligible aerodynamic interferences, whereas the helicopter is better at higher speeds, because of the drag penalty due to the larger rotor mast of the coaxial configuration.

In these comparisons, the arbitrary choice was made of comparing configurations with the same total weight and same rotor solidity. The goal was mainly to illustrate the effect of different rotor arrangements. However, these configurations have obviously different empty weights. Moreover, even if the considered payload is the same, the fuel weight will be different, not only because the required powers are different, but also because the engine is more likely to be different. Indeed, to take advantage of the tilt-rotor configuration, the useful power should be higher, which means a heavier engine. This preliminary study highlighted the fact that, for a deeper analysis of their flight performance, a more detailed weight breakdown assessment and the modeling of different engines (power, consumption and weight) are needed for a more comprehensive comparison of these configurations.

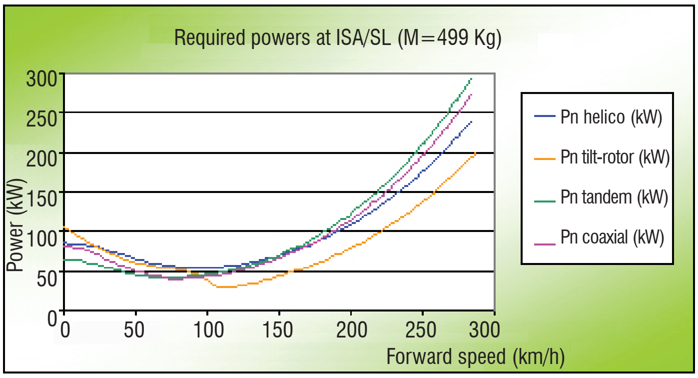


Figure 4 - comparison of the needed powers for the CAPECON coaxial configuration and the equivalent helicopter, tandem and tilt-rotor configurations (extract from [2])

MAVDEM

MAVDEM (Miniature Air Vehicle DEMonstrator) is a project funded by the European Defense Agency. This was a four year project (from September 2005 to September 2009) with a consortium composed of French (Onera and Alcore Technologies), Spanish (SENER), Italian (Oto Melara and Celin Avio) and Norwegian (TellMie) partners.

The objectives of the project are to define, build and flight-test a MAV configuration (less than 50 cm wingspan). This MAV should be capable of hovering and economic fast cruising, in order to perform infantryman support missions. Examples of such missions are open-field observation or city exploration.

In order to perform such missions, this MAV must combine two capabilities :

- Hovering, in order to look inside a building through windows, for example;
- Economic fast cruise, in order to cover the maximal area in a minimum of time, with the maximal endurance.

Those two objectives are conflicting and require the right trade-offs to be made, in order to meet the requirements in terms of endurance and velocity, which are rather challenging :

- Endurance requirement : 15 minutes hovering and 30 minutes of economic cruise ;
- Velocity requirement : 20 m/s as maximum speed.

One important issue for the success of the project was to choose a vehicle concept able to meet the requirements. The methodology proposed for this choice was to look at a wide spectrum of possible solutions, then to detail them and at last to choose the best vehicle to be built. The concepts that were analyzed were either taken from existing state-of-the-art designs or created.

Once potential candidate vehicle configurations had been identified, a three-stage selection process was made. It culminated with the final vehicle built (see figure 5). Each stage enables the design of the candidate configurations to be enhanced, as well as the least adapted ones to be discarded. This is described more in detail in the following paragraphs.

Figure 5 - Illustration of the vehicle configuration selection methodology

The first action of the vehicle configuration selection was to make a survey, as wide as possible, of the existing VTOL concepts. During the preparation of this survey, ideas arose and new original concepts were designed within the consortium. This survey ended with 26 candidate concepts, described by illustrative pictures, and the way to control them on all 3 axes. Then, a multi-criteria analysis was performed, in order to sort the various concepts. The selection was based on a limited number of criteria, divided into 4 main categories: performance, controllability/stability/maneuverability, complexity of design and safety (as shown in table 1). This analysis was not based on calculations, but rather on the expertise of the consortium. First a score was given, once per criterion, for each concept and then each criterion was weighted, in order to account for their relative importance, and a multi-criteria analysis was performed based on these values. The process, checked through alternative multi-attribute decision-making methods, ended in the selection of 5 concepts.

Performance	Hover endurance Lifting power at max. speed Propulsion power at max. speed
Controllability/stability/ maneuverability	Ease of control Degree of inherent stability Maneuverability
Complexity of design	Airframe complexity Aerodynamic shape Propulsion integration
Safety	Operator security Additional safety

Table 1 - Criteria for top-down selection

After this first selection, the level of detail had to be improved (up to the preliminary design), in order to perform a second selection aimed

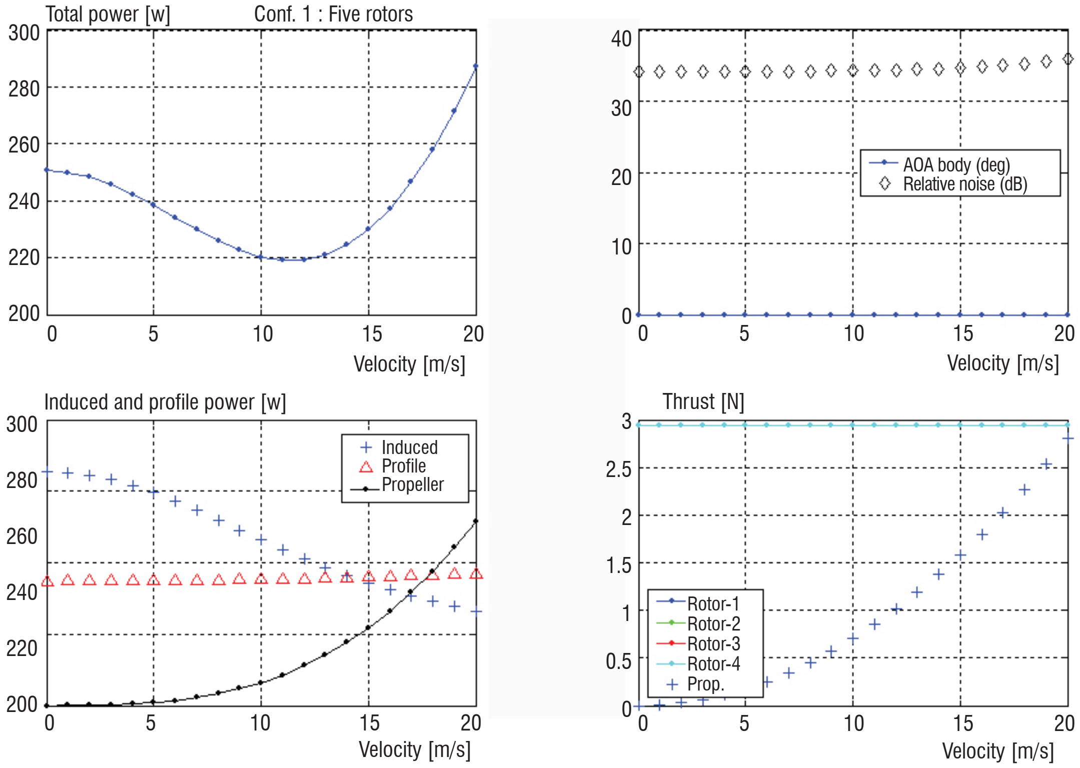


Figure 6 - Performance curves for configuration 1

at keeping only two concepts. This design improvement required several tasks :

- Identification and characterization (weight, dimensions and power consumption) of the required onboard components ;
- Propulsion considerations, especially in regard to battery volume and engine efficiency ;
- Aeroshape design refinement, with the associated estimated lift and drag ;
- Performance estimation.

Concerning this last point, the performance of each concept was calculated using a power balance method, all implemented using the Matlab software application. Several types of curves resulted for each configuration. Figure 6 shows an example of the performance curves.

All of these tasks enabled the design of the 5 retained configurations to be improved. The new designs are presented hereunder (table 2).

This situation led the consortium to decide to combine the best properties of the various configurations into 2 options : a 4-rotor concept (Configuration A) and a double coaxial rotor concept (Configuration B).

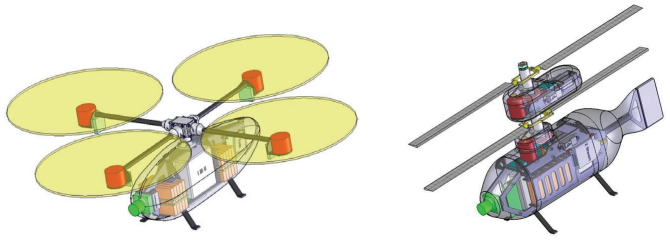
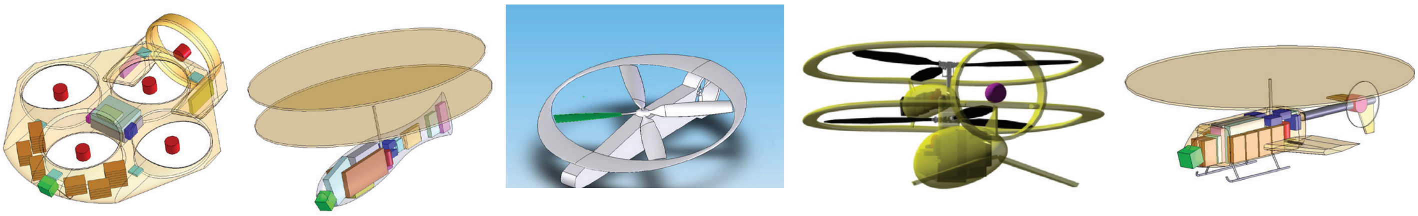


Figure 7 - Illustration of configurations A and B



Configuration 1
Configuration 2
Configuration 3
Configuration 4
Configuration 5

Table 2 - Preliminary design

Before selecting the final configuration to be built and flight tested, another improvement of the configuration designs was necessary. This design improvement included propulsion tests, in order to calibrate the calculation codes with actual values of power, efficiency, torque, etc. Various engines and propellers were tested, in order to choose the best-suited solution for each configuration.
In parallel to these propulsion tests, the structure and internal arrangement were more precisely defined. This design was performed by taking into account operational aspects, such as transport, battery removal and replacement, or manipulation by soldiers equipped with gloves.

Based on this "internal design", external fuselages were optimized to the least possible volume. CFD calculations have been performed to assess their lift and drag characteristics, as a function of the angle of attack (figure 8).

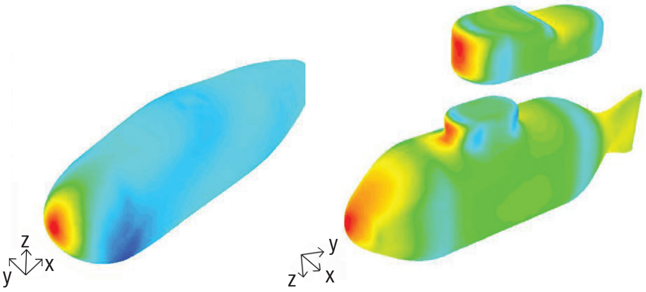


Figure 8 - Example of a CFD result for configurations A (left) and B (right)

A loop calculation of the estimated performance was made for both configurations, based on the experimental propulsion tests, the improved weight budget (from the structure definition) and the aerodynamic analysis. This performance estimation was performed in terms of endurance, which is the most challenging and dimensioning requirement, especially regarding the propulsion. Based on a new multi-criteria analysis and in agreement with the whole consortium, the retained configuration for the MAVDEM was the 4-rotor concept (figure 9).

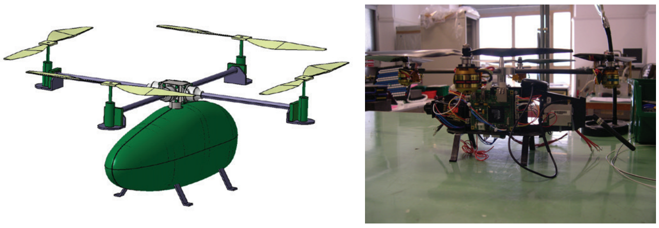


Figure 9 - Selected MAVDEM configuration (left) and partially built concept (right)

The goal of the MAVDEM project was to perform the preliminary conception until the Technology Readiness Level (TRL) 4 (i.e. flight test demonstration). This turned out to be too ambitious with respect to the time frame of the project MAVDEM ended at the software integration validation test stage, even though the previous steps were successfully reached (including individual hardware tests, system integration and guidance, and navigation and flight control software implementation).

Some conclusions can however be drawn from the MAVDEM experience, about the methods used for concept evaluation and pre-sizing. First of all, the MAVDEM process was sequential, i.e., at each level of the selection, new tools had to be selected and updated. Furthermore, specific difficulties arose at each step :

- For the multi-criteria analysis, the criteria table was built using the experts involved in the project and took some times to converge.
- For the second selection loop, specific developments had to be made on the existing tools, in order to take into account the various designs that were selected and an agreement had to be reached between the experts on the values of the tool parameters.
- For the last step, the High Fidelity calculations (C.F.D. and F.E.) were based on the choice of the experts and not driven by the choice of a specific surrogate model.

Therefore, the impact of the experts' judgment was significant in this project. The need is arising for a calculation platform that is less reliant on the direct involvement of discipline experts for the predesign and evaluation of rotorcraft concepts. Moreover, a numerical workshop or prototyping tool would allow these expert assessments to be capitalized in models and methods, as well as allowing design loops to be performed more systematically, with iteration rather than a sequential case-based process.

ExDro

Within the ExDro expert assessment (where ExDro stands for "Expertises Drones", 2008-2009) performed by Onera for the French Ministry of Defense, a work package was dedicated to the RW-UAV for both the Army and Navy. A significant part of the study was aimed at determining the best rotorcraft to respond to the requirements in terms of flight performance. For this purpose, two investigations were carried out :

- the evaluation of the proposals by three industrial consortiums with two helicopter UAVs based on the adaptation of two manned helicopters (the Orka based on the Cabri-G2 and the "Unmanned Mission Enhanced Little Bird" based on the A/MH-6X) and on the Bell Eagle-Eye Tilt-Rotor UAV ;
- the selection and pre-sizing of four different rotorcraft concepts, as well as their evaluation and comparisons regarding the mission specifications.

For evident confidentiality reasons, the expert assessment of the rotary wing air vehicles proposed by industry will not be discussed here. Moreover, the second part of this study is more relevant to the topic of this paper. This work on alternate rotorcraft concepts was done in three steps:

- Step 1 : the review of the different types of rotorcraft bringing out their main strengths and weaknesses, and the pre-selection of four concepts potentially well suited for the missions of both the Army and Navy ;
- Step 2 : the pre-sizing of these four concepts up to a level of description, allowing the use of the available analytical tools for the flight performance computation;
- Step 3 : the evaluation and comparisons of the flight performance of these four rotary wing air vehicles regarding the military mission specification.

The four pre-selected concepts were: a helicopter capable of reducing the revolution speed of the main rotor in flight (as in the case of the Hummingbird A160 RW-UAV), a coaxial rotorcraft, a tilt-rotor tilt-wing concept (as in the case of the Erica concept for reducing the downwash of the rotors on the wings), a compound helicopter with a pair of wings and a vectored thrust device at the rear (as, for example, in the case of the Piasecki Pathfinder and X-49A Speedhawk).

Of course, the purpose here is not to go into the details of the pre-sizing of these four RW-UAVs, but rather to sum up the main common points in terms of the methodological approach.
For every pre-sizing exercise, the starting point and the ending description level must be clearly defined. In this ExDro case related to VTOL UAV, the pre-sizing had to be done from scratch (voluntarily ignoring the air vehicles proposed by industry) and the goal was to obtain a rough draft of the main characteristics of the aircraft allowing the flight performance calculation using the power balance method. For each concept, the input data for that kind of calculation had to be determined: Maximum Take-Off Weight (MTOW), engine data (weight and provided power with respect to the altitude and temperature), rotor characteristics (radius, number of blades, mean chord, rotational speed, etc.), fuselage or airframe data (drag and sizes), wing data (for calculating their lift and drag, in the case of the tilt-rotor and compound configurations).

A common starting point was obviously the payload, since all of these RW-UAVs had to carry the same mission payload. This was completed by an estimation of the weight of all of the other on-board equipment. Taking into account the equipment configuration with the highest demand in terms of weight, the maximum on-board equipment weight (W_{PL} including here the payload and all of the equipment) was set. From that entry, a statistical approach was applied, like the one presented in [4], for example.

After checking that our own rotorcraft database provided results similar to those given in [4], the following logical chain was used for the derivation of the main rotorcraft characteristics.

The first key parameter to be determined is the take-off gross weight W_0. Knowing by statistics the ratio W_{PL}/W_0 for a certain type of rotorcraft concept and W_{PL} from the requirements, W_0 can be estimated. As illustrated in the scheme in figure 10, from this key parameter can be derived: on the one hand, the take-off power, the engine and the main weight breakdown, as well as, on the other hand, the lifting rotor characteristics and the main airframe dimensions.

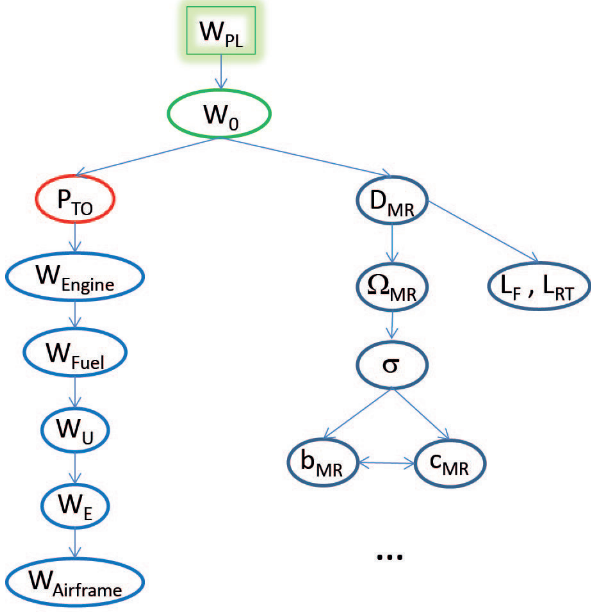


Figure 10 - Example of a logical chain for pre-sizing (MR for Main Rotor)

For the weights, the notation and definition are :

$$W_0 = W_U + W_E$$
$$W_0 = (W_{useful\_load}) + (W_{empty\text{-}weight})$$
$$= (W_{payload} + W_{fuel}) + (W_{engine} + W_{airframe})$$

P_{TO} is the take-off power, from which, by using an engine database, a first choice of engine can be made giving its weight and specific consumption. The fuel weight can then be calculated knowing the mission requirements and typical specific consumption values. The payload, fuel, engine and gross weights being known, the airframe weight can be deduced.

From the design gross weight (W_0), the lifting rotor diameter (D) can be estimated by an analytical expression from the statistics (see figure 10). The fuselage length (L_F) and the rotorcraft over-all length (rotors turning L_{RT}) can then be assessed, also by statistics. The disk loading is defined by : $T/S = W_0.g/(\pi.R^2)$, where R is the rotor radius. By dimensioning the lifting rotor(s) for the most demanding flight case (e.g., hovering at the highest take-off altitude), which sets a certain value of the air density (ρ), and with typical values for helicopters in terms of mean blade lift coefficient ($Czm = 0.6$) and blade tip Mach number ($M = 0.6$), the blade rotational tip speed ($\Omega.R \cong 200\ m/s$) and the rotor solidity can be calculated :

$$\sigma = \frac{6}{\rho(R\Omega)^2}\frac{1}{Czm}\frac{T}{S}$$

By definition, the rotor solidity is the ratio of the surface of blades over the rotor disk surface:

$$= \frac{b.c.R}{.R} = \frac{b.c}{.R}$$

The rotor radius being known ($R=D/2$), if the number of blades (b) is chosen, for example for a coaxial the minimum number of blades is four (two by rotor), then the mean chord (c) can be calculated. Otherwise, the blade aspect ratio can be first estimated (R/c) and then the number of blades can be deduced.

These main characteristics having been assessed, the power balance method can be applied for a first evaluation of the rotorcraft performance. This second stage may lead to the adjustment of some parameters and/or to another choice for the engine. Therefore, the pre-sizing and the flight performance assessment must be viewed in a loop with iterations.

Of course, this logical chain must be adapted to the rotorcraft concept considered. This simple approach gives a very first rough draft in a conservative way. That is to say, for known rotorcraft concepts with a significant number of examples in the database. However, a strength of this basic method is that the more complex trade-off requiring a wider scope of multidisciplinary models, as well as higher fidelity models, is however implicitly included. Indeed, even at this very early stage of the predesign, the use (in the database) of existing concrete flying rotorcraft, that have reached their full development, allows the constraints and disciplinary inter-dependences involved later in the preliminary conception process to be anticipated.

However, the statistical approach has the obvious drawback of being conservative by nature, i.e., limited to the rotorcraft concepts present in the database. Moreover, the validity ranges of the key parameters, (gross weight, sizes, etc.), are in principle limited to the maximum and minimum values available in the database: applying the design trends beyond these limits entails extrapolation. Therefore, this method is not suited for the innovation of new concepts or the exploration of existing configurations beyond the currently known limits.

In addition to their own contributions to a specific issue and to the general problem of RW-UAV pre-sizing, these first studies have brought forward the need for a more global multidisciplinary approach and a more comprehensive analysis, including flight performance, safety, environmental impact … They have paved the way toward the definition and construction of a general analysis tool for rotorcraft concepts.

Present : the CREATION project

Rebounding after different studies like the ones previously presented showing recurring needs in this field, a first attempt was made for setting-up methods and tools (see [5]). But definitely for going further, the expertise of several scientific departments must be involved.

CREATION is an Onera multidepartment project launched in January 2011 for a four years period. CREATION means "Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network". The main goal is to build a numerical platform for the analysis and evaluation of the flight performance and environmental impact (noise and air pollution) of rotorcraft concepts.

The ambition is high, because the evaluation tool must be applicable to any kind of rotorcraft concept, whatever its description level. This last requirement means that the platform must be able to cope with the difficult problem of pre-sizing from scratch, that is to say, when only an idea of a concept has to be explored and/or when only the mission requirements are known.

However, the building of the platform has been scheduled in a pragmatic way, increasing the complexity step by step with realistic milestones:

- Milestone 1 - **evaluation** capability: setting up modules and workflows for the case of an existing helicopter,
- Milestone 2 - **pre-sizing** capability: setting up models and methods for the case of a new helicopter, to be defined from its mission requirements,
- Milestone 3 - **innovation** capability: generalizing the platform to alternate rotorcraft and applying it for an innovative concept.

Framework

The numerical platform CREATION is a computational workshop with models and methods. The models contain the knowledge from the various disciplines and they are the suitable evaluation tools for the available data. The methods correspond to the know-how for using the models together as tools for the evaluation, pre-sizing and innovation purposes.

First, the framework is presented here, i.e., the organization and implementation. Then, the main features of models and methods will be summarized.

From the general specifications, certain important features are derived for the organization of the platform. It must be composed of multidisciplinary modules, as well as multi-modeling levels inside each module.

Seven first main disciplinary modules have been identified as the "seven pillars". Two are central within the tool; they can be called "goal modules":

- Flight performance ;
- Environmental impact (acoustics, air pollution, etc.).

Around this bipolar structure of the tool, five "means modules" are present for providing the means for the flight performance and pollution evaluations:

- Missions & Specifications
- Architecture & Geometry
- Weights & Structures (including aeroelasticity)
- Aerodynamics
- Power Generation (engine).

The platform could be enriched later with other modules, depending on specific needs (e.g., regarding mission payload) or on other evaluation criteria or constraints (airworthiness regulation, economic viability, etc.). Safety, and in particular autorotation capability, must be assessed through criteria suited to the level of description of the rotorcraft and to its characteristics ("manned or unmanned" type, gross weight, etc.).

Except for the "Missions & Specifications" module, which provides the flight conditions with respect to the requirements and to the mission profile, several modeling levels have been implemented within each of the other disciplinary modules. This multi-modeling level feature is needed to adapt the "modeling granulometry" to the considered level of detail in the data describing the rotorcraft. Four main modeling levels are currently used :

- Level 0 : Response Surface Models (RSM) based on databases or simulations ;
- Level 1 : simple analytical models based on physics ;
- Level 2 : more comprehensive analytical models ;
- Level 3 : numerical models.

The more the model is complex, the more it is time consuming in terms of computational time, but also the more demanding it is in terms of required data inputs. The Response Surface Models or more generally reduced models are useful, not only for decreasing the computational time, but also for reducing the amount of input data. The modeling complexity and the number of needed inputs vary according to each other.

Therefore, this vertical structure in modeling levels is also fully justified and useful in the pre-sizing process. Indeed, when a predesign must be done from scratch, its definition must be made from the lower models to the upper models, increasing the data describing the aircraft step by step. In the current state of the tool, for the Onera purposes, the starting point is the initialization of the pre-sizing with Level 0 models; then a first pre-sizing loop is performed at Level 1 and the description of the rotorcraft is progressively enriched until Level 3 is reached. Thus, in the current state of development of this tool, the final definition stage of the pre-sizing is actually when all of the data needed for using a numerical rotorcraft flight mechanics code has been defined. More precisely numerical means here that the main rotor model is based on a blade element approach allowing a fine description of the blade properties (geometry, aerodynamics, inertia, etc.).

In order to give a concrete image of this computational workshop, it can be seen in a 3-Dimensional space as a building (see figure 11).

NFM : Numerical Flight Mechanics
AFM : Analytical Flight Mechanics
BP : Balance of Power

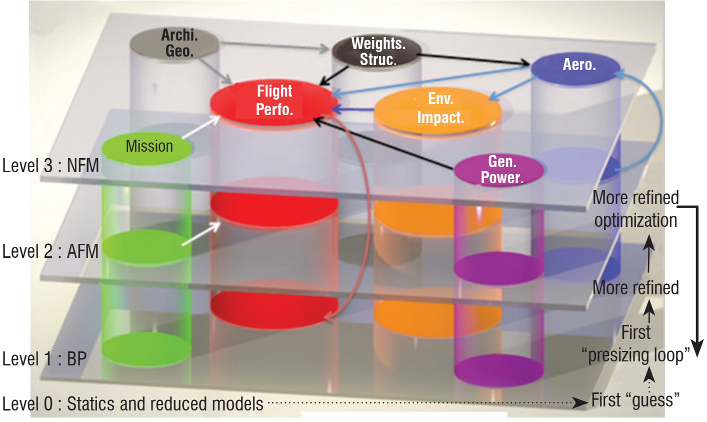


Figure 11 - A 3 dimensional view of the CREATION computational workshop

In its current state, the workshop has four floors corresponding to the modeling levels with Level 0 in its basement and seven pillars corresponding to the disciplinary modules.

The approach is to begin the evaluation of a rotorcraft from the modeling level consistent with the available data describing it. If the rotorcraft exists and all of the required data is known, the evaluation can be performed with the highest modeling level. Otherwise, the evaluation starts from the appropriate level and, if a more detailed evaluation is required, an enrichment of the data can be proceeded to, through a bottom-up process. On the contrary, if no data is available, an "ab initio" pre-sizing must be done. Level 0 provides "first guess" rough estimates of the main data, which are then recalculated and completed with other data in a first pre-sizing loop at Level 1. More refined optimizations are performed at the upper modeling levels, for improving the assessment of this data and/or for the pre-sizing of other parts of the rotorcraft. Macro iterations between these various pre-sizing loops are needed to ensure the consistency of the global optimization.

For example, in the case of the helicopter pre-sizing, Level 0 allows the process to be initialized based on design trends from a database. At Level 1, the main data describing the fuselage and the main rotor is calculated within a multi-objective optimization loop. Then, at Level 2, the complete equilibrium of forces and moments resulting at the rotorcraft center of gravity can be considered with a comprehensive analytical flight mechanics model allowing the pre-sizing of the rear components (horizontal stabilizer, fin and tail rotor). At Level 3, a more refined predesign of the main rotor blade (twist, airfoils, chords, etc.) can be performed, using a rotor blade element model. From this, a new rotor polar (blade mean drag versus mean lift and speed) can be computed, for example, therefore the results of the upper level optimizations can be fed back into Level 1 for a new round of optimization up until the convergence of the whole process has been reached.

The arrows appearing in figure 11 are just to illustrate the connections between the disciplinary modules. The workflows between the models, in terms of data exchanges (inputs/outputs), must be determined by establishing the diagram of the dependencies required for a certain application, depending on the available data and on the modeling level. Data flows between the modeling levels are also used, for example when an upper level model provides a reduced model to a lower level model, or in the bottom-up enrichment of data.

Models

A comprehensive and detailed description of the models is beyond the scope of this paper. First, descriptions have been given in [6] and [7]. Here, only the main common characteristics of these models are highlighted.

In each of the involved disciplines (flight mechanics, aerodynamics, acoustics, structures etc.), Onera has been developing for years expert models based on physics, constantly improving their fidelity by taking into account new results or experimental data. These high fidelity models are very demanding in terms of input data. They are not suited for the evaluation of a rotorcraft described only by few items of data or for pre-sizing studies. Their computational cost is too high for exploring a design space. Moreover, the large amount of inputs required for using these complex models prohibits their application at an early design stage.

Therefore, in the CREATION project, the disciplinary experts were asked to provide simplified models corresponding to the defined modeling levels. This is clearly an added value of the project, to develop simplified models working with few items of data and yet allowing a realistic assessment of the flight performance, as well as the acoustic and air pollution of any rotorcraft. This is a challenging task and the main approaches for developing this kind of models will be summarized hereafter.

Note that the complexity of a model is not a guarantee of its high fidelity. There are of course two kinds of uncertainties: those arising from the model itself (equations, formulations) and those arising from the input data. Using a complex expert model at an early evaluation stage can lead to lower fidelity results than using a simpler model with the few available items of data.

Various approaches have been applied to set these simplified models. They can be based on databases, on simulation results and on physics. For example, a database on existing rotorcraft (about 260) has been gathered, but also a database on aeronautical engines (turbine, piston, electrical) and acoustics based on helicopter certification measurements. Simulation results from upper level models can be used to derive simpler models at lower levels. This is for example the case of the aerodynamic rotor model giving the blade mean drag with respect to the blade mean lift and advance ratio. The formulation is based on physics with three terms: a basic drag, a drag due to airfoil flow separation and stall effects, and a drag due to compressibility effects, completed by a factor for the Reynolds effect. A representative number of simulations with a rotor blade element model are performed, from which the various parameters of the surrogate model are deduced.

Various mathematical techniques are used to generate these reduced models, such as statistical and polynomial regression, kriging, neural network, etc. More than the choice of mathematical method in these meta-modeling tasks, an important point is often to inject physics as far as possible into the model structure. The disciplinary expert must be able to set the formulation to represent the most important physical effects relevant for the evaluation and consistent with the available data. Therefore, most of the simplified models are based on physics with parameters tuned by using databases obtained from experiments or simulations. Some models result from a hybrid approach, like in the weight module in which some parts are assessed based on statistics (equipment, crew and passengers, etc.) and others with models based on physics (blades, rotor, mechanical transmission, etc.). Some models are Response Surface Models: for the same inputs giving output values as close as possible (with a known precision) to the results given by one or several interacting more complex models.

These reduced models not only decrease the computational time, but also have a reduced set of suited inputs and outputs consistent with the available data at each modeling level.

Methodologies: MDO formulations and optimization techniques

The CREATION platform, like other tools aimed at designing an aerial vehicle, exhibits some multi-disciplinary particularities:

- it incorporates a large number of disciplines that are, sometimes, strongly coupled and must cope with a high number of variables;
- it has several levels of modeling, ranging from statistical tools to high-fidelity ones, thus requiring the use of reduced models;
- it requires a detailed exploration of the design space to be enabled, together with the capability to identify the global optimum of the entire system.

An engineering system method field, aimed at handling several disciplines more efficiently, has been developed to tackle those particularities: the Multidisciplinary Design Optimization (MDO). The objective of the MDO methods is to take advantage of the couplings and the synergies between the various disciplines, in order to achieve the global optimal design. The main targets of the MDO process are the quality of the solution found, the computation time and the robustness of the optimization process (i.e., the ability to converge to an optimum from a large initialization domain). Therefore, by solving the MDO problem early in the design process and taking advantage of advanced computational analysis tools, designers can simultaneously improve the design and reduce the time and cost of the design cycle. Onera has been investigating this field of research since 2004, with a 4 year internal project called DOOM ("Démarche Outillée d'Optimisation Multidisciplinaire" or Multidisciplinary Optimization Tooled Approach) and has made significant studies and achievements in this domain (see [8] and [9]).

When talking about MDO, the first step is to overcome the analysis problem that one wants to solve, that is so say, to identify the disciplinary couplings and the computation of objectives and constraints as a function of the design variables.

Once it has been done, the next step is to formulate the problem, in order to be able to use suitable optimization algorithms, which mean to select the most suitable MDO architecture. The MDO architecture defines both how the different models are coupled and how the overall optimization problem is solved. The architecture can be either monolithic or distributed. In a monolithic approach, a single optimization problem is solved. In a distributed approach, the same problem is partitioned into multiple sub-problems containing small subsets of the variables and constraints. More information on the MDO architectures can be found in [10].

Concerning the CREATION process, some monolithic approaches, such as MDF (MultiDiscipline Feasible) and SAND (Simultaneous Analysis and Design) have been evaluated. These studies have shown that the computational time required to reach an acceptable convergence was far too high for rotorcraft concept exploration. Moreover, the will to use higher fidelity models, in order to introduce more knowledge at early stages of the design process, will increase this computational time. A common way to lower the computational cost is to make smart use of the most advanced modeling tools, using response surface modeling. The meta-models (or surrogate models) the most used in the engineering field aerospace systems are for example : polynomial regression techniques, the kriging statistical model, artificial networks or radial basis functions. All of these meta-modeling techniques differ in terms of degrees of freedom, type of base functions and learning technique, thus leading to various areas of application. Within the CREATION platform, two different kinds of surrogate model were investigated : the kriging statistical model and the MOE techniques (Mixture Of Experts), combining several surrogate models [11]. They both enabled the computational time to be greatly reduced, while achieving a good accuracy in regard to the optimal solutions.

At the time of this paper, the CREATION workshop has been built by dealing with manned – inhabited rotorcraft. An example of an application is presented in [12] for a large civil transport helicopter. For that case, the objectives were to minimize the required fuel weight, the empty weight and the noise produced on the ground during the landing approach. The choice of objectives is case dependent. For a RW-UAV this can be, for example: the required engine power, the empty weight and some crucial performances for the applications considered (endurance, range or a certain speed for best endurance, best range or maximal speed). For rotorcraft pre-sizing, it is often a question of compromise between the hover and forward flight performance. This is why the objectives or criteria are generally : the hover efficiency (Figure of Merit, i.e., ratio between the ideal minimum needed power corresponding to the theoretical induced power according to the momentum theory P_{i0} and the actual required power for hovering, which is the sum of the induced power P_i plus the blade airfoil drag power P_{blade}) and the propulsive efficiency (equivalent lift over drag ratio for a lifting rotor: ratio of the weight W multiplied by the cruise speed V with respect to the total needed power P_{req}).

$$FM = P_{i0} \,/\, (P_i + P_{blade}) \text{ and } L/D_e = W.V/\, P_{req}$$

The design parameters depend of course on the kind of rotorcraft concept. However, the number of rotors, as well as the radius, number of blades, mean chord and rotation speed of each rotor, are the main parameters to be optimized.

Moreover, some adaptations are needed, especially on the aerodynamic and weight models, before coping with the case of the small scale RW-UAVs.

Conclusion and perspectives
Future : RW-UAS presizing

Examples of past studies regarding RW-UAVs evaluation and pre-sizing have shown a clear need for numerical tools combining multi-disciplinary models and multi-objective optimization methods.

An internal Onera project was launched in 2011 to respond to this kind of need and, more generally, to address the evaluation of any kind of rotorcraft concept, first and mainly from the flight performance and environmental impact points of view. A computational platform called CREATION has been developed, integrating multidisciplinary modules within multi-modeling levels, together with methodologies to cope with problems involving multi-design variables (continuous or discrete), multi-objectives and constraints related to multi-missions, etc...

The last milestone of this project is the innovation capability. The differences between uninhabited and inhabited air vehicles have been highlighted in the reference book [13], showing that the field of possible solutions is wider in the UAV case. A high potential for innovation exists in the field of RW-UAVs. Hence, a good candidate as a demonstration exercise will be to deal with the pre-sizing of an innovative RW-UAV. Note that an innovative RW-UAV concept could inspire an innovative manned – inhabited rotorcraft and reciprocally. This is for example the case of the multi-rotor UAV concept (quad-, hexa-, octo-, etc. rotors), which recently gave birth to a version with pilot onboard: the Volocopter and its eighteen electrical rotors.

Of course, the library of models must be enriched and adapted to better take into account, for example, small scale effects like the Reynolds phenomenon. Beyond that, developing a methodology for giving to the tool the ability to produce new concepts not predefined by the engineer is really a challenging task. This assumes the combination of various components (lifting and propulsive devices, airframe, etc.) and the evaluation of the resulting performance taking into account their mutual interaction.

Another aspect of the tool development is the enrichment of the criteria used for the evaluation. Obviously, the evaluation starts with the performance in stabilized flight. However, this will be extended to maneuvers and flight dynamics first related to safety and airworthiness regulations, as well as stability and controllability. This will require more integration, taking into account the Control System design as soon as possible in the overall predesign process, to assess the Uninhabited Aircraft System (UAS) as a whole ■

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Acronyms

CAPECON	(Civil UAV APplications & Economic Effectivity of Potential CONfiguration solutions)
CFD	(Computational Fluid Dynamics)
CREATION	(Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network)
ExDro	(Expertises Drones)
FE	(Finite Element)
FM	(Figure of Merit (hover efficiency for a rotor))
HALE	(High Altitude Long Endurance)
MALE	(Medium Altitude Long Endurance)
MAVDEM	(Miniature Air Vehicle DEMonstrator)
MDO	(Multidisciplinary Design Optimization)
MOE	(Mixture of Experts)
MTOW	(Maximum Take-Off Weight)
RW	(Rotary Wings)
TPP	(Tip-Path-Plane)
TR	(Tilt-Rotor)
TRL	(Technology Readiness Level)
UAS	(Uninhabited or unmanned Aircraft System)
UAVs	(Uninhabited Aircraft Vehicles)
VTOL	(Vertical Take-Off and Landing)

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