



Open Archive Toulouse Archive Ouverte (OATAO)

OATAO is an open access repository that collects the work of Toulouse researchers and makes it freely available over the web where possible.

This is an author-deposited version published in: <http://oatao.univ-toulouse.fr/>
Eprints ID: 11308

To cite this version: Moschetta, Jean-Marc *The aerodynamics of micro air vehicles: technical challenges and scientific issues*. (2014) International Journal of Engineering Systems Modelling and Simulation, vol. 6 (n° 3/4). pp. 134-148. ISSN 1755-9758

Any correspondence concerning this service should be sent to the repository administrator: staff-oatao@inp-toulouse.fr

The aerodynamics of micro air vehicles: technical challenges and scientific issues

Jean-Marc Moschetta

Department Aerodynamics, Energetics and Propulsion,
Institut Supérieur de l'Aéronautique et de l'Espace,
10 Avenue Edouard Belin,
F-31400 Toulouse, France
E-mail: jean-marc.moschetta@isae.fr

Abstract: Micro air vehicles raise numerous design problems associated to the size reduction: lower aerodynamic and propulsion efficiencies, higher sensitivity to atmospheric turbulence, low-density energy of electric propulsion, etc. The paper discusses some of the most important design issues and analyses the aerodynamic challenges encountered in the field of MAVs. A number of novel aerodynamic configurations combining rotors and fixed-wing are proposed and discussed in order to recover efficiency and maneuverability at low speeds.

Keywords: micro air vehicles; MAVs; low-Reynolds aerodynamics; tilt-body; convertible aircraft; propeller-wing interaction; coaxial rotors.

Reference to this paper should be made as follows: Moschetta, J-M. (2014) 'The aerodynamics of micro air vehicles: technical challenges and scientific issues', *Int. J. Engineering Systems Modelling and Simulation*, Vol. 6, Nos. 3/4, pp.134–148.

Biographical notes: Jean-Marc Moschetta is a Professor of Aerodynamics in the Department Aerodynamics, Energetics and Propulsion at the 'Institut Supérieur de l'Aéronautique et de l'Espace' (ISAE). He graduated from SUPAERO in 1987. He received his PhD in 1991 and received the Habilitation thesis in 2000. In 1994–1995, he was invited as a Visiting Professor at Caltech, California. In 2011, he founded the Micro Air Vehicle Research Centre in Toulouse which now networks nine research laboratories involved in MAV technologies.

1 Introduction

Micro air vehicles (MAVs) also known as micro-drones may be defined as uninhabited micro aircraft capable of completing surveillance or recognition missions in outdoor or indoor environments. Although a lot of attention has been paid so far to the embedded system which includes sensors, autopilot and a payload, MAVs have now reached a level of maturity such that the problem of improving their aerodynamic performance is now becoming a major concern. Because of severe Reynolds effect limitations, designing MAVs cannot just mean downsizing conventional aircraft. Instead of mimicking nature which actually did not produce the rotating motion (with few exceptions), it is rather advisable to consider combinations of rotors with fixed-wings in order to achieve good aerodynamic performances and ease of technological development.

2 MAV design issues

Designing MAVs does not revert to scale down conventional aircraft configurations. In level flight, the lift equation equates the vehicle weight and the lift force as

$$mg = \frac{1}{2} \rho S V^2 C_z \quad (1)$$

while mass m and wing surface S vary as L^3 and L^2 respectively, where L is the vehicle maximum dimension. Therefore, the flight speed V reduces as

$$V \sim \sqrt{L} \quad (2)$$

while C_z remains almost constant. As a consequence, the Reynolds number Re based on the wing chord varies as

$$Re \sim L^{3/2} \quad (3)$$

which means that the Reynolds number diminishes faster than the vehicle size. Namely, reducing the vehicle size by a factor of two leads to a Reynolds reduction by a factor of 3. Low-Reynolds effects dramatically affect both the aerodynamic efficiency and the propulsion efficiency as it will be described in the next section.

In addition to the Reynolds number reduction, MAVs have to face a greater sensitivity to atmospheric perturbations. That is also a consequence of the size

reduction although equation (2) tends to damp the effect. As it is driven by aerodynamic forces which are proportional to S , the equation of motion is given by

$$m\ddot{x} = F = \frac{1}{2}\rho SV^2 C_z \sim V^2 L^2 \sim L^3 \quad (4)$$

Provided that mass also reduces as L^3 , it follows that the trajectory sensitivity to atmospheric perturbations is not intrinsically affected by the size reduction. However, since the vehicle inertia J reduces as L^5 , it follows that

$$J\ddot{\theta} = M = \frac{1}{2}\rho SV^2 LC_m \sim L^4 \quad (5)$$

where θ refers to some angle (pitch, roll or yaw) which describes the vehicle attitude. Since $J \sim L^5$, it follows that

$$\ddot{\theta} \sim L^{-1} \quad (6)$$

which indicates that the vehicle attitude around its centre of gravity will be greatly affected by the size reduction. In practice, the picture is much more serious since the average atmospheric perturbations near the ground (typically 2–5 m/s) becomes comparable to the average MAV flight speed which ultimately means that flying an MAV in urban environment is like flying a jetliner through a cumulonimbus cloud.

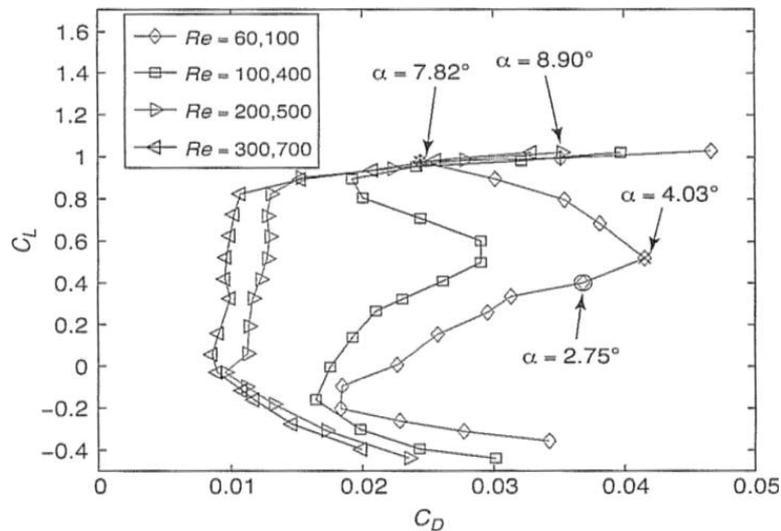
Another consequence of mass reduction is that thermal combustion engines fail to offer a practical solution to the low endurance problem. While the heat produced in the combustion chamber is proportional to L^3 , the heat flux dissipated through its walls only reduces as L^2 . Consequently, miniaturising thermal engines will inevitably lead to poor thermodynamic efficiencies since most of the heat produced within the combustion chamber will rapidly evaporates through the walls. Increasing the rotation speed

to compensate for heat losses will not bring a viable solution either because of limitations on the chamber residence time. Furthermore, poor pressure tightness and friction increase are additional problems which also ruin the attractiveness of thermal combustion engines when reduced in size (Sher et al., 2009). MAVs designers are therefore left to the sole choice of electrically powered vehicles which suffer from a limited specific energy of a maximum value of 200 Wh/kg for a high quality Lithium-polymer battery.

3 Low-Reynolds airfoils

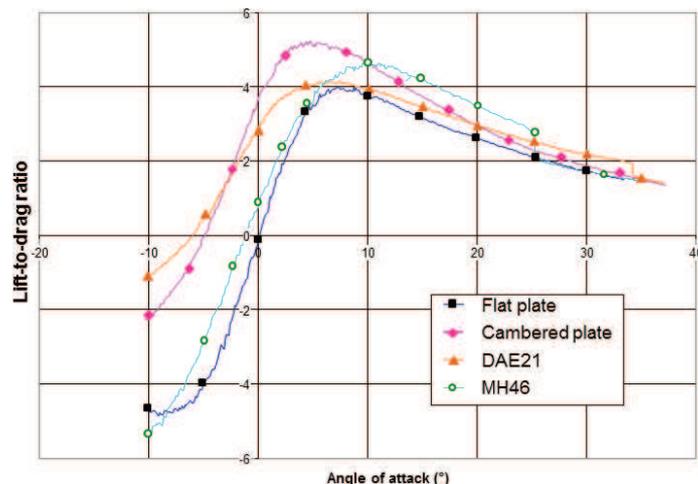
Numerous papers have been published so far on low-Reynolds airfoils. As reported by McMasters and Henderson (1980), the low-Reynolds airfoil performance dramatically decreases below a chord Reynolds number of the order of 100,000, which is a typical Reynolds number encountered by a fixed-wing MAV of 15 cm chord flying at 10 m/s. The unfortunate thing is that the flight regime where MAVs fly is a very critical regime in which it is difficult to predict whether the boundary layer is going to be laminar or turbulent. According to Lissaman (1983), the lift-to-drag ratio of smooth airfoils may decrease more than an order of magnitude near the critical Reynolds number. That is due to the fact that, according to Carmichael's (1981) rule, the Reynolds number based on the laminar bubble length is comparable to the Reynolds number based on the wing chord, which means that the laminar bubble may cover a significant part of the wing. In order to reduce the influence of laminar bubbles, some benefit may be obtained from the use of transition strips or roughness effects to increase the lift-to-drag ratio in the critical regime.

Figure 1 Typical 'zigzag' effect on the Eppler E374 airfoil polar computed at various chord Reynolds numbers



Source: After Shyy (2008)

Figure 2 Comparison of experimental lift-to-drag ratios for different wing airfoils of aspect ratio 1 (see online version for colours)



As reported by Shyy (2008), instead of the familiar C-shape of high-Reynolds number airfoils, the lift-drag polar of low Reynolds-number airfoils exhibit a typical ‘zigzag’ pattern which may affect the overall MAV performance (Figure 1). For instance, the Eppler E374 airfoil at an angle of attack of 2.75° exhibits a long laminar bubble which extends on the airfoil upper surface and creates a large drag. When the angle of attack is further increased, the long bubble suddenly shortens as a consequence of the Tollmien-Schlichting wave which triggers transition and an attached turbulent boundary-layer flow. As a result, the drag is significantly reduced (around an angle of attack of 7.82°). Finally, when the angle of attack is further increased, the turbulent boundary layer can no longer sustain recompression and a massive separation occurs, with a substantial drag increase.

A final noticeable feature of low-Reynolds airfoils is that thin cambered airfoils of the WWI airplanes family appear to outperform thick airfoils such as the DAE21 or the MH46 low-Reynolds airfoils both in maximum lift coefficients and in maximum lift-to-drag ratios. Figure 2 illustrates that effect on a series of low-aspect ratio wings based on different airfoils and tested in a low-speed wind tunnel at ISAE.

4 Fixed-wing aerodynamics

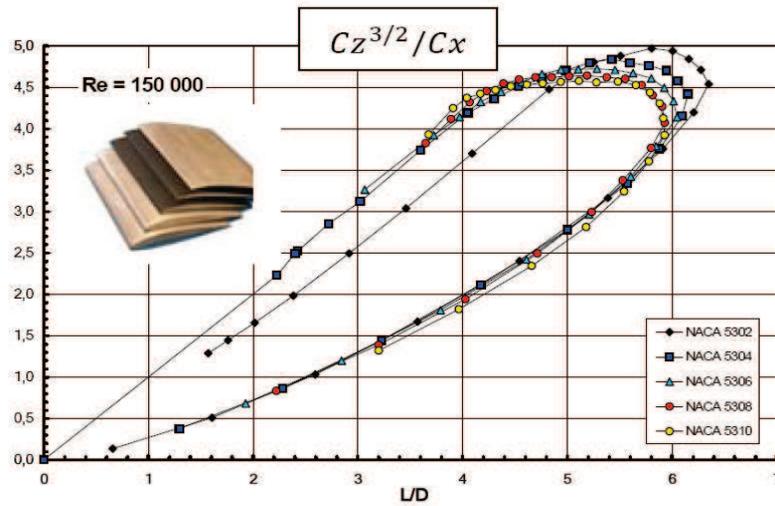
Because of the chord Reynolds number limitation combined with drastic wing loadings, fixed-wing MAVs usually consist of a flying wing with an aspect ratio between 1 and 2. At such low aspect ratios, the effect of airfoil selection may appear as less important for the overall aerodynamic performance due to overwhelming 3D effects. In order to assess the importance of the airfoil selection, a set of five rectangular wings of aspect ratio 1.6 has been fabricated using five different airfoils of constant relative camber (5%) but varying thicknesses ranging from 2% to 10%. The maximum camber location of all five wings is

30% and a 4-digit NACA series definition has been used for the five wings: NACA 5302, 5304, 5306, 5308 and 5310. The idea was to avoid mixing the airfoil camber effect with the thickness effect. All wings were mounted on a three-strut setup connected to a 3-component balance measuring lift, drag and pitching moment for angles of attack ranging from -2.5° to 32.5° with a step of 1° . Figure 3 illustrates the effect of airfoil thickness at constant camber on the aerodynamic performance of the rectangular wing. As expected in the low-Reynolds number regime, thinner airfoils yield better aerodynamic performances, both in terms of power coefficient $C_z^{3/2}/C_x$ and in terms of lift-to-drag ratio. However, stall is slightly delayed when thickness is increased. At a Reynolds number of 150,000, increasing thickness does not drastically affect the aerodynamic performances above 8%. That means in practice that if a thicker airfoil has been selected in order to accommodate on-board equipment for instance, there is no interest in choosing an intermediate value for the thickness.

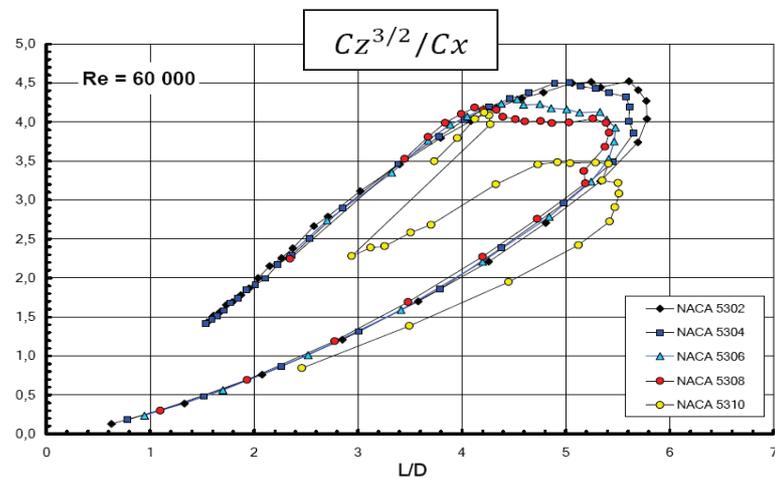
At a lower wing chord Reynolds number (60,000), the picture is more subtle to interpret. Thinner airfoils still display higher aerodynamic performances than thicker ones but thicker airfoils (e.g., 10%) show very poor performances with the consequence of the zigzag effect already described in Section 3. That effect should be taken care of when the Reynolds number is decreased below 100,000. In that case, it is important to consider using either very thin airfoils or, alternatively, thick airfoils with vortex generator or transition strips.

In view of the stringent mass limitation, MAV designers generally tend to use the largest possible wing surface within the maximum size limitation. For a given maximum vehicle size, that strategy yields a circular wing planform which aspect ratio is equal to $4/\pi$ or approximately 1.273. However, it has been shown that increasing the aspect ratio at constant maximum dimension by shrinking the circle into an ellipse leads to a decrease of the total drag at constant lift (Figure 4).

Figure 3 Power coefficients as a function of lift-to-drag ratio for five rectangular wings (AR = 1.6) of varying thicknesses (2% to 10%), wing chord Reynolds number (a) 150,000 and (b) 60,000 (see online version for colours)



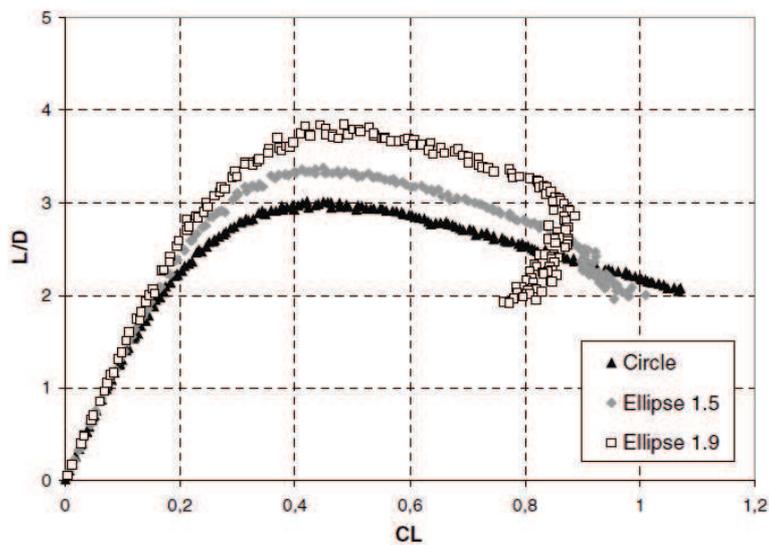
(a)



(b)

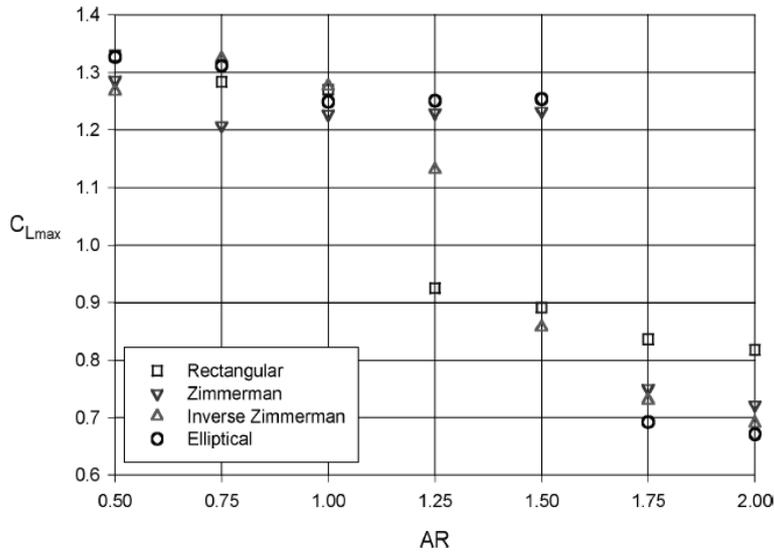
Source: After Blanc et al. (2008)

Figure 4 Experimental lift-to-drag ratios of different elliptical wing at various aspect ratios



Source: Moschetta and Thipyopas (2007)

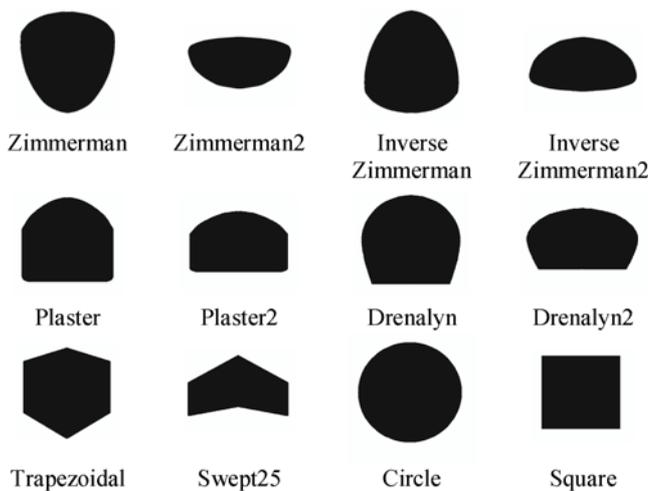
Figure 5 Maximum lift coefficient of various wing planforms and different values of the aspect ratio



Source: Experimental results after Torres and Mueller (2004)

That is because both the wetted area decreases, which reduces the friction drag, and the aspect ratio increases which reduces the induced drag. Therefore, the circular wing planform is not the optimal one although it remains very popular. Yet, if the chord is further reduced, severe limitations occur in terms of load factor due to the drop in maximum lift coefficient as illustrated in Figure 5. That limitation dramatically affects the vehicle capability to sustain high-lift flight phases such as landing or banked turns. As a conclusion, an aspect ratio of around 1.5 to 2 appears to be a good trade-off between maximum lift-to-drag ratio and manoeuvrability.

Figure 6 Various wing planforms tested in ISAE low-speed wind tunnel



Note: Forward flight direction upwards.

Source: After Moschetta and Thipyopas (2007)

Over the last 20 years, many wing planforms have been tested in the low-Reynolds regime, including circles, ellipses, rectangles, Zimmerman wings (Torres and Mueller,

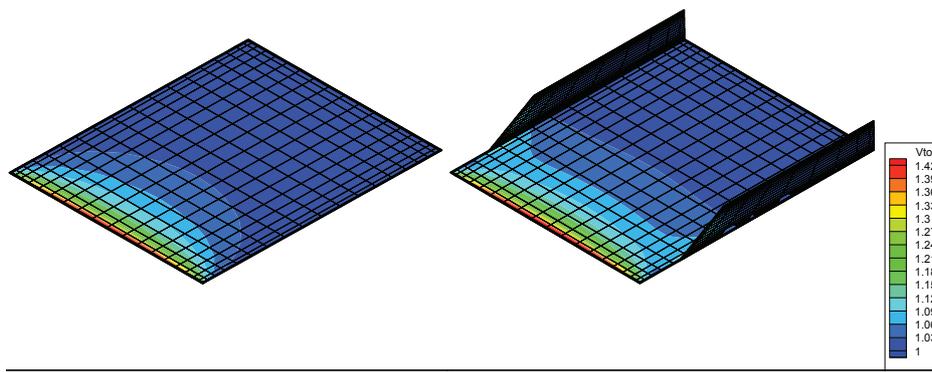
2004) and other options (Moschetta and Thipyopas, 2007; Hammons and Thompson, 2006). Although the Zimmerman's wing is generally considered as the best performing wing planform for MAVs, the 'Plaster2' wing, with an aspect ratio of 1.8 appears to provide a slightly better maximum and cruise lift-to-drag ratio. A Plaster wing is formed by joining a half-ellipse and a rounded-corner rectangle at the quarter chord (Figure 6).

An additional advantage of the Plaster wing is that it has straight wing tips on which winglets may easily be adapted. Adding winglets on either side of the wing slightly increases the parasite drag but also significantly increases the effective angle of attack near the wing tips which results in higher aerodynamic efficiency as reported by Viieru et al. (2005). It also provides lateral stability since winglets may play the role of a tail. A flying version of the plaster was tested in June 2003 with a radio-controlled prototype of 64 grams and a 'Plaster2' wing of 14.5 cm root chord and 23 cm span (Figure 7).

Figure 7 The monoplane flying wing *Plaster* designed at ISAE (see online version for colours)

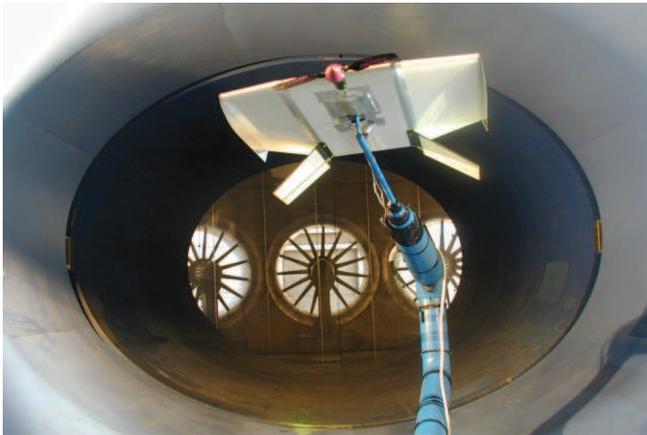


Figure 8 Winglet effect on the pressure distribution over a square wing using a vortex lattice method (see online version for colours)

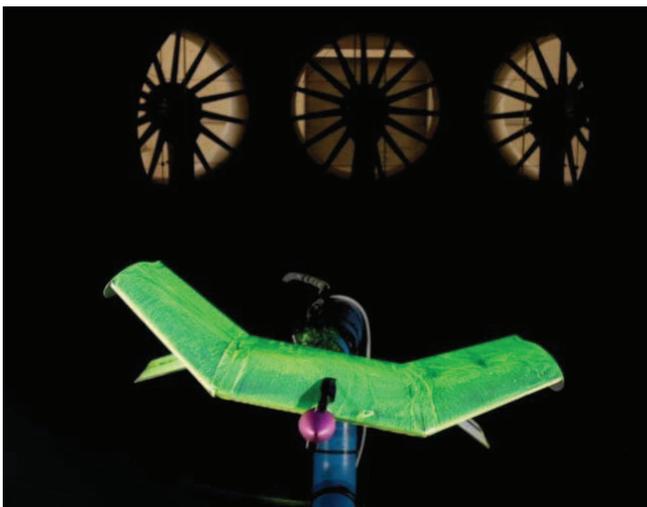


Source: After Pardi (2005)

Figure 9 (a) Monoplane MAV ‘*Kiool*’ in the ISAE S4 low-speed wind tunnel (b) Oilflow visualisation showing intense vortical structure on the wing leeward side (see online version for colours)



(a)

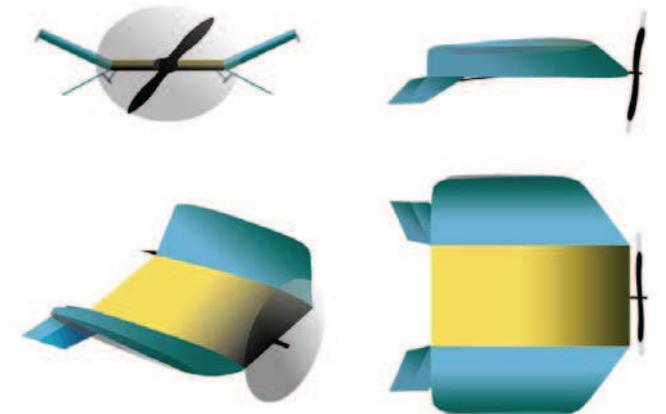


(b)

Both numerical and experimental investigations were conducted at ISAE to assess the benefit of winglets of various shapes on a simple rectangular wing. The results indicate that adding winglets along the wing tips artificially

increases the wing aspect ratio by reducing the effective induced drag and increases aerodynamic performance in spite of a slight friction drag penalty (Figure 8).

Figure 10 The *Minus-Kiool* MAV (57 g, 20 cm) (see online version for colours)



One of the major aerodynamic problems related to flying wing is to obtain static longitudinal stability and high maximum lift at the same time. As an alternative to the *Plaster* flying wing which mainly consists of a thin airfoil, another monoplane wing has been considered in parallel to

provide some room for the on-board electronic equipment. In order to let the main wing unaffected by control surfaces, the new idea was to exploit the third dimension by adding V-shape stabilisers under the wing. The stabilisers would then provide control in pitch and roll as well as lateral stability without affecting the aerodynamic efficiency of the main wing (Figure 9).

Further size reduction was then investigated to fabricate a flying prototype of less than 60 grams with 20 cm span (Figure 10). The main wing is made of a rectangular central part of 14 cm span and 8 cm wing chord. On either side of that central part, two trapezoidal wings of 6.5 cm width are connected to the central part with a positive dihedral angle of 25°. A 30° sweep angle is applied along the side wings leading edge. That prototype was successfully flown in 2002. It was launched by a portable catapult and equipped with a miniaturised video camera.

5 Biplane MAVs

Because of the restrictive dimension constraints, the induced drag of monoplane flying wings represents up to 70% to 80% of the overall drag in cruise conditions. Biplane configurations provide a classical way to reduce the induced drag by doubling the monoplane wing surface while complying with the maximum constraint defined by the sphere in which the vehicle should fit. The major effect of biplane wings is roughly to divide the induced drag by a factor of 2 at the price of a parasite drag increase. In the case of MAVs where the induced drag plays a major role in the total drag, it turns out that the drag penalty due to the additional interference and parasite drag is compensated by the induced drag reduction if the lift coefficient is greater than some minimum value. Interference drag is the drag generated by the aerodynamic interaction between both wings, while parasite drag includes the additional drag due to the connecting structure. As illustrated in Table 1, the biplane configuration yields a substantial increase both of the maximum lift-to-drag ratio as well as of the cruise lift-to-drag ratio.

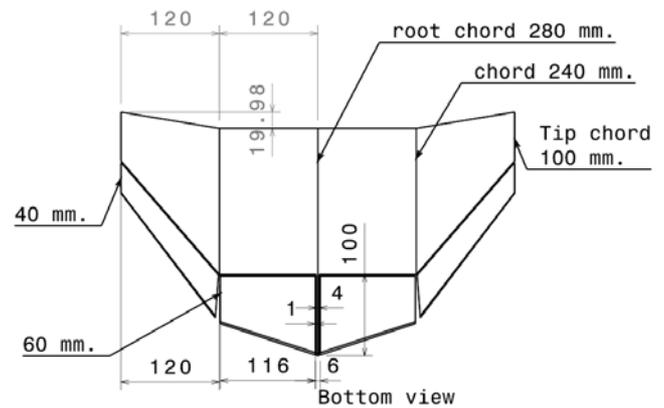
Another advantage of the biplane configuration is that it can nearly retrieve the maximum lift coefficient produced by a monoplane wing of aspect ratio 1. As an attempt to compare two MAV configurations at a given maximum dimension constraint, a biplane bimotor MAV called *Avilent* has been designed and tested in the S4 low-speed wind tunnel at ISAE [Figure 11(a)]. The *Avilent* is made of two wings in tandem configuration which fit into a 51 cm diameter sphere. Two counter-rotating propellers are located

along the upper wing trailing edge and three control surfaces are distributed along the lower wing trailing edge to provide control in pitch and roll. Using counter-rotating propeller cancel the resulting torque due to moving parts and allows for a broader blowing effect along the wing span. The *Avilent* configuration combines an upper wing and a lower wing connected by two vertical struts equipped with counter rotating motors in pusher configuration. Both wings are based on a S1223 airfoil designed by Selig and Guglielmo (1997) for the low-Reynolds number regime. The upper wing is a 48 cm span wing with a 25 cm root chord and two trapezoidal side wings attached on either side of a 24 cm span central part of rectangular planform. Both side wings are 12 cm wide with an 8 cm tip chord.

Figure 11 (a) The *Avilent* biplane-bimotor MAV configuration (b) Schematic view of the lower wing (see online version for colours)



(a)



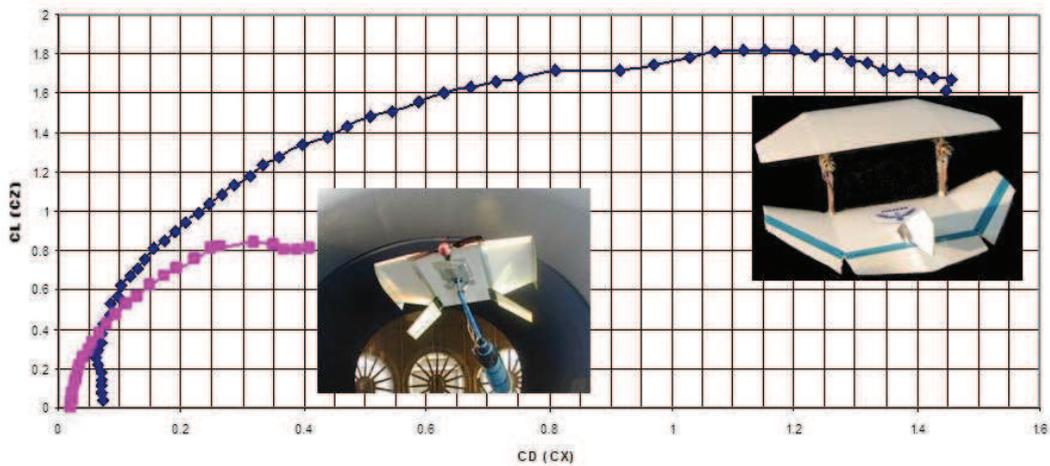
(b)

Table 1 Experimental aerodynamic performances of monoplane and biplane wings

Wing configuration	A	C_{Dmin}	k	C_{Lmax}	$L/D_{(cruise)}$	$L/D_{(max)}$
Monoplane	1	0.055	0.54	1.25	3.89	4.04
Monoplane	2	0.042	0.33	0.59	4.38	5.11
Biplane	2	0.066	0.27	1.06	5.19	5.48

Source: Moschetta and Thipyopas (2007)

Figure 12 Aerodynamic polars of monoplane and biplane MAVs of equal maximum dimension (see online version for colours)



The lower wing is described on Figure 11(b). It consists of a central part equipped with two side wings with a dihedral angle of 20° and a 9.5° negative leading edge sweep angle. The upper wing is tilted with a positive angle of 5° with respect to the lower wing and the vertical distance between both wings is equal to 17 cm. As illustrated in Figure 12, the biplane configuration leads to a much greater maximum lift coefficient and a higher lift-to-drag ratio when the cruise lift coefficient is greater than 0.5.

Because the *Avilent* maximum lift coefficient is twice as high than the *Kiool* monoplane configuration (Thipyopas and Moschetta, 2009), the vehicle can sustain low-speed flight which is unusual for a fixed-wing configuration. Yet, because the propeller slipstream only interacts with the leeward side of the lower wing, vertical flight remained difficult to achieve. Therefore, following the same idea, another biplane bimotor configuration was designed in order to maintain the control surface efficiency even at very low speed. In order to achieve that, a third horizontal tail was placed in the propeller slipstream [Figure 13(a)].

In the *TYTO* concept (Thipyopas et al., 2007), both upper and lower wings are connected by lateral winglets which surround the propellers, protecting the airframe and enhancing the overall vehicle rigidity. The upper wing is a 30 cm span semi-circular wing equipped with two motors located along the trailing edge in pusher configuration. The lower wing is described in Figure 13(b). A flying prototype version controlled by the Paparazzi autopilot developed at ENAC has been successfully flown in 2007. The MAV, called *TYTO30*, is a 30 cm span airframe equipped with a 2-axis video-camera fitted into a ping-pong ball (Figure 14).

Figure 13 (a) A powered wind tunnel model of the *TYTO* MAV, rear view (b) Lower wing planform (see online version for colours)

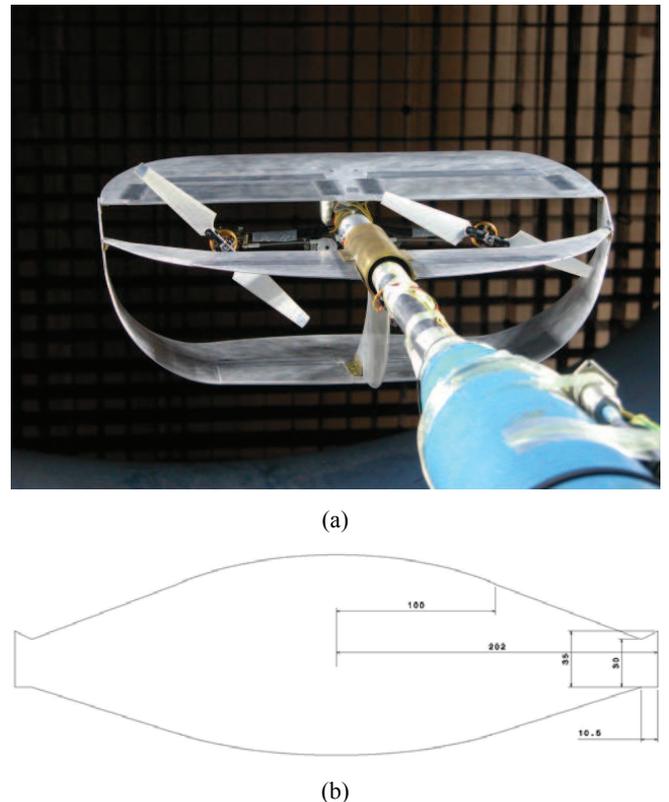
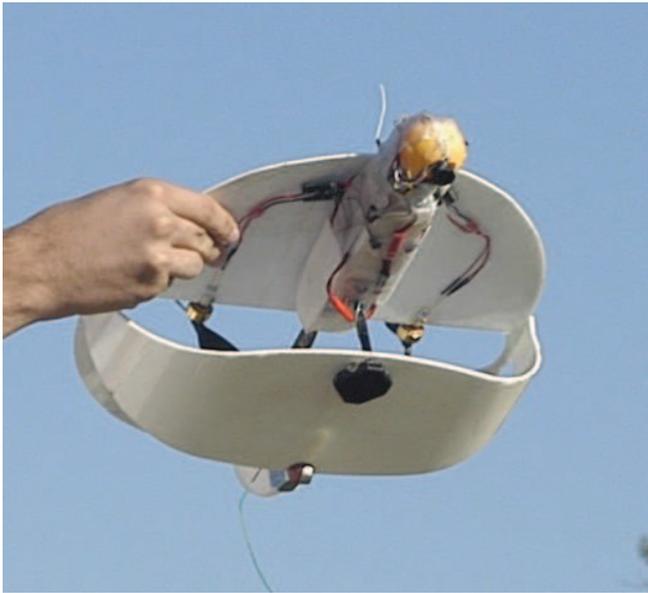


Figure 14 The *TYTO30* MAV before take-off (see online version for colours)



Source: After Blanc et al. (2008)

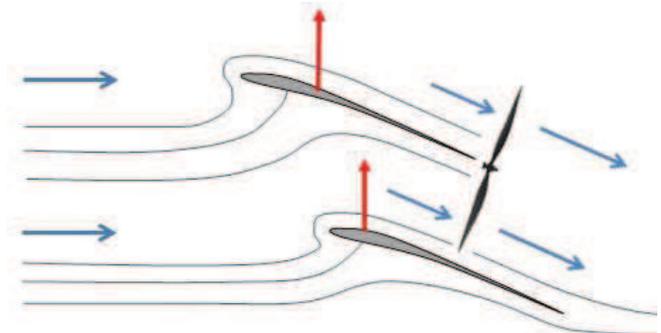
Although no specific flight tests were carried out to check the vehicle capability to sustain hover flight, the *TYTO30* MAV has the capability to achieve very low speeds over targets. As opposed to the monoplane flying wing which requires a double camber airfoil for a positive pitching moment at the aerodynamic centre, the biplane configuration allows to design the upper wing with a positive camber airfoil. Positive camber airfoils can achieve a higher maximum lift coefficient while the horizontal stabiliser ensures longitudinal equilibrium. The tandem wing configuration with counter-rotating propellers located along the upper wing trailing edge has been the best of several combinations of upper and lower wings, including different motor arrangements. If the propellers are located along the wing leading edge, the effective angle of attack is lower so is the circulation created around the wing. Although the propeller-induced speed increases the lift, the effective angle of attack is decreased accordingly. As a result, the lift force created on a wing located downstream the propeller is lower than the lift force created by a pusher configuration (Figure 15).

6 Coaxial MAV configurations

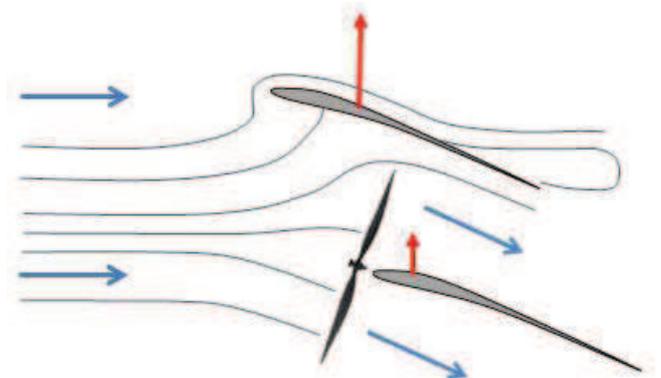
While the biplane or tandem wing concept was not initially developed so as to allow for hover flight, it proved to be able to achieve very low-speed flights which could correspond in practice to mission steps where the vehicle is hovering over the target in order to transmit clear images to the ground station. In order to achieve a multi-tasking mission including a fast horizontal flight followed by a stationary flight over a point of interest, two opposite conceptual design strategies are available. The first strategy consists of modifying an airplane configuration so as to

decrease its minimum flight speed. That first strategy has been followed from the monoplane flying wing up to the *TYTO* concept. The second strategy consists of considering the vertical flight as a starting point and modify the concept so as to achieve horizontal flight. That second strategy has been followed in parallel and is described in the present section. The result of that strategy has led to the general idea of the tilt-body concept. With the objective of achieving hover flight with a combination of fixed-wing and propellers, it quickly appears that using counter-rotating propellers is a reasonable design basis which cancels the resulting torque and the gyroscopic effects associated with single propeller aircraft. One option is to consider coaxial rotors which have the main advantage that the rotor diameter can extend up to the maximum vehicle size. By using the largest possible disk space for the coaxial rotor, one can limit the negative effect of down-sizing rotors which generally result in poor figures of merit because of the drastic Reynolds number reduction. The very first idea on coaxial rotor was developed at ISAE as the *BR2C* concept (Steenbakker et al., 2008). The *BR2C* configuration was a long-ducted coaxial rotor in which the shroud was designed with a divergent shape generating lift through recompression in the lower part (Figure 16).

Figure 15 (a) Tandem wing with propellers in pusher configuration (b) tandem wings with propellers in tractor configuration (see online version for colours)

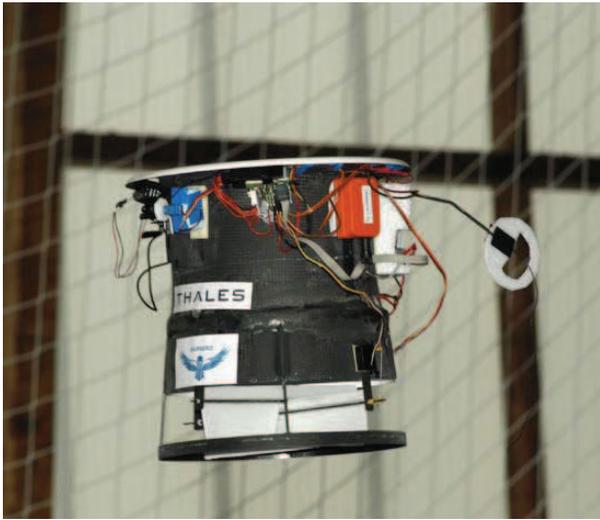


(a)



(b)

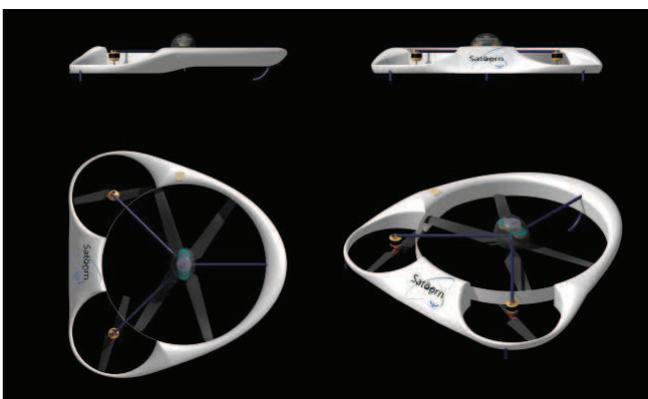
Figure 16 The *BR2C*: a ducted-fan coaxial MAV (see online version for colours)



Source: Steenbakker et al. (2008)

The main design idea in the *BR2C* MAV was to compensate the weight penalty due to the addition of the outer structure by generating some additional lift so that the total mass budget was kept constant. In addition, the duct significantly increases the birotor efficiency because of a reduction in tip losses. The inlet shape also plays an important role in the total lift force since the inlet round shape creates a low pressure zone which further increases the lift (Huo et al., 2011). Control in pitch and roll was obtained by two flaps located below the birotor. Although long-ducted birotors are suitable for indoor missions, they are very sensitive to crosswind conditions and therefore are unlikely to handle outdoor flights. As a consequence, a short-ducted birotor was designed to reduce the lateral surface in crosswind conditions. The *Satoorn* MAV was then designed and flown at ISAE as illustrated in Figure 17.

Figure 17 The *Satoorn*: a short ducted-fan coaxial MAV (see online version for colours)



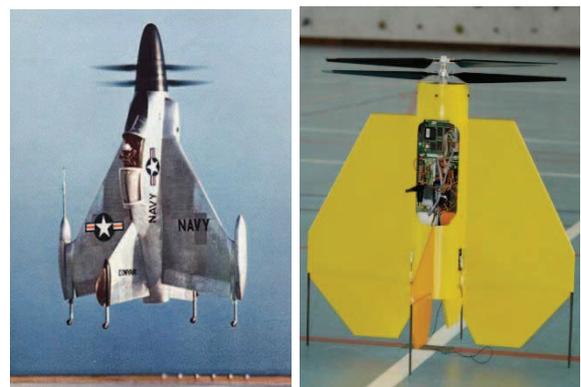
In order to control the *Satoorn* in pitch and roll, two smaller rotors were added in the rear part of the vehicle. The *Satoorn* was successfully flown outdoors but suffered from strong nonlinearities due to the aerodynamic interactions

between the main coaxial rotor and the control rotors as described by Thipyopas et al. (2008, 2010).

7 The tilt-body concept

In order to achieve either translation flight or vertical flight, different options are available. One is to directly tilt the rotors or the wing located in the rotor slipstream such as in the V-22 'Osprey' configuration. In the field of MAVs, the AVIGLE developed at Aachen University is an example of such a concept which requires an additional rotor above the horizontal tail in order to control the pitching moment (Holsten et al., 2011). Furthermore, it requires a tilting mechanism in the airframe which leads to a significant weight penalty. At ISAE, another option has been followed. It was inspired by the Convair 'Pogo' XFY-1 developed in the 1950s in the USA [Figure 18(a)]. The main idea is to tilt the entire vehicle to perform transition flight. In horizontal flight, the vehicle may behave like a regular airplane while in vertical flight it may hover like a helicopter. A first tail-sitter mini-UAV called *Vertigo* was developed and flown in 2006 at ISAE [Figure 18(b)].

Figure 18 (a) The Convair 'Pogo' vs. (b) the mini-UAV 'Vertigo' (see online version for colours)



(a)

(b)

Source: After Bataille et al. (2009)

The *Vertigo* was powered by a coaxial rotor located in tractor position and equipped with two main wings and two smaller wings in the other direction. Control in pitch, roll and yaw was obtained by elevators located on all four wings while the counter-rotating propellers were constantly blowing onto the control surfaces to maintain an equilibrium throughout transition between horizontal and vertical flight (Bataille et al., 2009). A downscaling of the *Vertigo* led to the mini-*Vertigo* developed at ISAE in collaboration with the University of Arizona (Figure 19). While the *Vertigo* wings were made of mere flat plate airfoils, the *mini-Vertigo* (30 cm span) was equipped with a Zimmerman's wing and radio-controlled through gyro stabilisation for a total mass of less than 200 grams. It proved to be very capable of fast forward flight as well as vertical flight (Shkarayev et al., 2008).

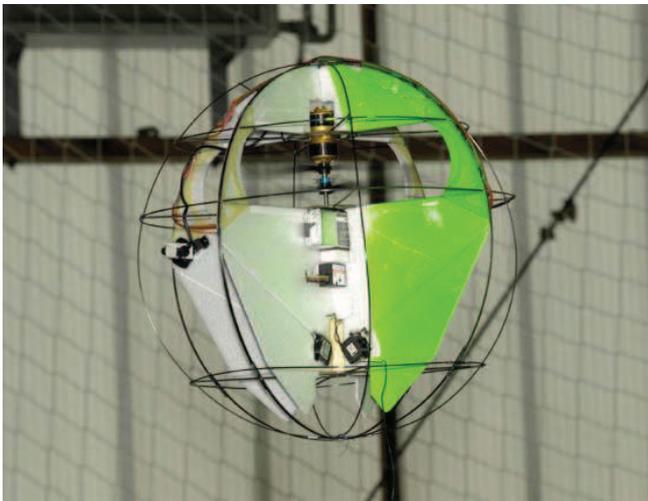
Figure 19 The *mini-Vertigo*: a coaxial fixed-wing MAV (see online version for colours)



Source: After Shkarayev et al. (2008)

Because of its exposed rotors in tractor position, the *mini-Vertigo* was still very vulnerable to collisions and crashes. A first attempt to provide a ‘crashproof’ airframe arose from the idea of a sphere made of carbon rods. The *Vision* was then developed and flown on the occasion of the MAV07 competition held in Toulouse in 2007 (Figure 20).

Figure 20 The *Vision*: unducted coaxial fixed-wing MAV (see online version for colours)



The *Vision* had a genuine indoor flight capability and proved to be robust enough so as to be able to roll on the ground, although not in a controlled mode. It was still ill-suited to outdoor flights and a modified version of the *Vision*, called *Vision’Air*, was then designed and fabricated at ISAE (Figure 21). In the *Vision’Air* concept, several modifications were applied. First, the hollow shaft mechanism used in the *Vision* and the *Mini-Vertigo* were replaced by two outrunner brushless motors with propellers directly attached to the rotating part. Placing the birotor within the protecting airframe allowed to use any motors and opened the way for further miniaturisation. Second, some significant lifting surface was added upstream the

coaxial rotors. The idea was to deflect the flow in front of the rotors which increased the rotor efficiency. It also helped to increase the lift during transition instead of placing all lifting surfaces downstream the coaxial rotors where the effective angle of attack remains low. Finally, an airfoil was added onto the lifting surface located downstream the coaxial rotors so as to improve the aerodynamic performance in horizontal mode.

Figure 21 *Vision’Air*: a compact MAV for transition flight (see online version for colours)



More recently, another tilt-body prototype has been designed in view of finding the appropriate trade-off between aerodynamic performances for horizontal flight and vertical flight, while keeping in mind the idea of a protective outer structure. The *MAVion* was initially designed to be a reasonably good airplane, capable flying outdoors and easy to replicate as opposed to more complicated tail-sitters (Stone, 2008). The main design guidelines were simplicity and transition flight capacity. In order to provide a significant aspect ratio (between 1.5 and 2), it was decided to investigate the classical bimotor flying wing concept (Figure 22).

Figure 22 *MAVion*: a fixed-wing bimotor MAV for transition flight (see online version for colours)



Source: Itasse et al. (2011)

The rotation directions for the counter-rotating propellers were selected so as to artificially increase the aspect ratio by rotating in the opposite direction of wing vortices. That choice proved beneficial to start bank turns since, for instance, when turning right, a greater rotation speed applied to the left motor would not only produce a right-turning yaw moment but also a right-turning roll moment. In 2011, an indoor version was developed and patented with the use of free carbon wheels which played a protecting role for the airframe as well as a mean to roll. The MAVion ‘roll and fly’ was then capable of landing, waiting for a while, rolling on the ground and remotely taking off without human interaction. The ‘roll and fly’ concept also revealed its capability to roll and fly along walls and ceilings (Figure 23).

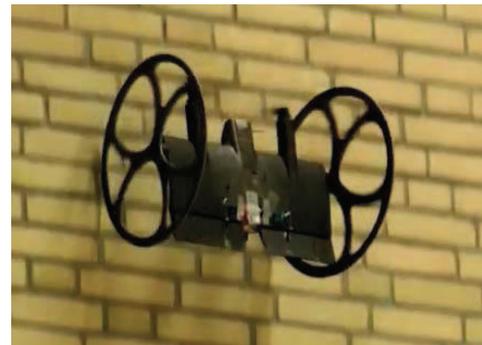
A fully-fledged autonomous version has been developed at ISAE including a video micro-camera or a 24-gram micro thermal camera for night recognition missions (Itasse et al., 2011). The propellers were chosen so as to achieve either forward flight up to 24 m/s or hover flight with a typical endurance of 15 minutes. In terms of aerodynamic performance, there are still open problems such as:

- 1 maintaining hover flight in strong crosswind conditions
- 2 rolling along a ceiling.

In situation 1, the vehicle will tend to tilt horizontally when the crosswind gets stronger, hence reducing its projected

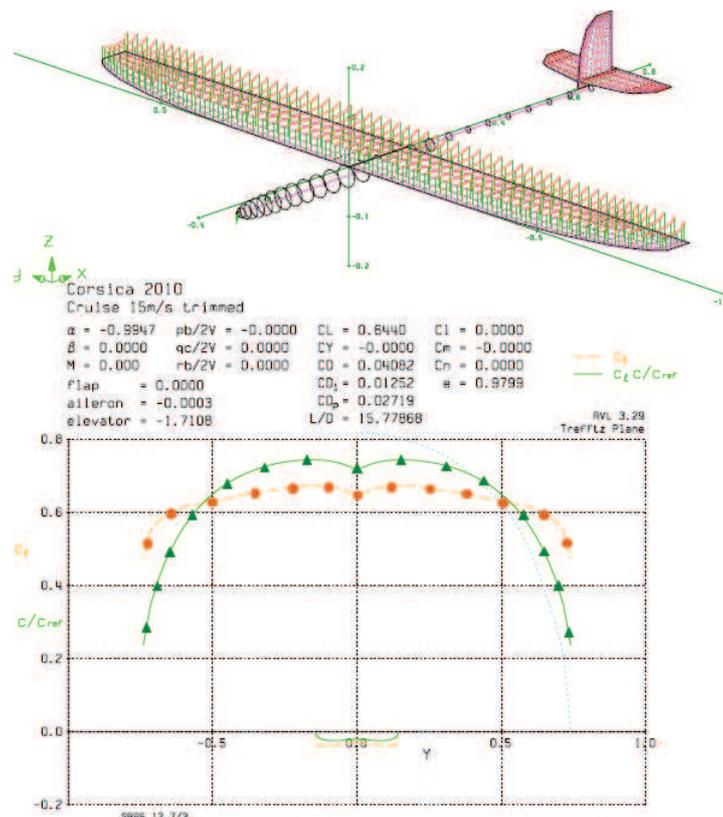
area. Ongoing developments include the capability to switch to a strong wind mode in which the MAVion could hold its attitude sideways with respect to the lateral wind. A collective pitch mechanism is also an option that is currently under investigation in order to adapt the blade pitch to either airplane or helicopter mode. Situation 2 may become difficult when the rotors are very close to the ceiling because the incoming flow is drastically constrained by the wall boundary condition. Increasing the wheel diameter may improve unstable behaviours in rolling phases but that would also involve adding mass to the vehicle.

Figure 23 The MAVion ‘Roll & Fly’ climbing along a vertical wall (see online version for colours)



Source: Itasse et al. (2011)

Figure 24 The lift distribution over the SPOC wing and its optimised horizontal tail (see online version for colours)



Notes: Distribution of local lift coefficient (orange dots) and local circulation (green triangles)

Source: After Bronz et al. (2010)

8 Long endurance MAVs

So far, mini-UAVs have been limited to short-range surveillance missions. Recent investigations showed that mini-UAVs can actually perform long-endurance surveillance missions if properly designed (Bronz et al., 2009). As a first attempt to do so, a mini-UAV of 1.6 m span was designed in view of flying over the Mediterranean Sea from Menton, France to Calvi, Corsica, which is a 185 km journey. According to the Laitone-Naylor theorem (Laitone, 1978) which shows that the overall induced drag in cruise conditions is minimum when the horizontal tail produces almost no lift, a mini-UAV called 'spirit of corsica' (*SPOC*) was designed and fabricated. Its total mass was less than 2 kg with 1.3 kg lithium batteries fitted into the wing. The wing was based on the SB96 airfoil and designed so as to produce uniform aerodynamic loads and avoid stall at wing tips (Figure 24).

A specific performance study was conducted to optimise the propeller and wind tunnel tests showed that the airplane had the capability to fly up to 250 km at a constant speed of 15 m/s. Current development include a new long-endurance concept of 1 m span, called *Eternity* (Figure 25) which is expected to fly as long as four to six hours with a solar-cell powered version. The airplane has been successfully flown in 2012 and is currently being equipped with the Paparazzi autopilot developed at ENAC.

Figure 25 The 1 m-span *Eternity* mini-UAV developed at ISAE and ENAC (see online version for colours)



Source: After Bronz et al. (2013)

A joint PhD thesis has been started in 2011 in collaboration between ISAE and the University of West of England, UK, to extract energy from the environment such as dynamic soaring. The main idea of that thesis is to learn from the Albatross flight and to apply the principles to a long-endurance mini-UAV through a new navigation strategy.

9 A new wind tunnel for MAVs

A new low-speed wind-tunnel devoted to MAV studies has been inaugurated in 2009 at ISAE. Its closed wind test section is 1.2 m × 0.8 m with a length of 2.4 m (Figure 26).

Figure 26 The ISAE variable pitch-fan wind tunnel for the study of MAVs (see online version for colours)



Glass windows have been provided in view of future PIV measurements and a 3D positioning system has been added to hold the models through a 5-component sting balance. The low-Reynolds wind-tunnel, called *SabRe*, is powered by a variable-pitch fan which allows controlling the flow speed and uniformity through the fan rotation speed as well as the fan blade pitch in running conditions. Although MAVs are generally flown in the turbulent atmospheric boundary layer where the turbulence intensity can vary from 0 to infinity (Watkins et al., 2009; Loxton et al., 2008), the *SabRe* turbulence level is only 0.2% at 3 m/s. The wind speed can vary from 2 to 25 m/s which corresponds to the typical MAV flight regime. The ISAE MAV wind tunnel can therefore accommodate scale 1 powered MAVs radio-controlled from outside (Figure 27).

Figure 27 Wind test section with the *MAVion* model at scale 1 (see online version for colours)



10 Conclusions

The current development of MAVs has opened the way to various configurations according to the different remote recognition missions to be accomplished. The combination of proprotors with fixed-wing is believed to be a very fruitful source of promising configurations which do not

require the complexity of flapping-wing technology. Even long-endurance performance can be expected from well-designed mini-UAVs. Finally, the most promising configurations for practical applications seem to be the tilt-body configurations either based on coaxial rotors or tandem rotors. Furthermore, the addition of a protecting structure can be beneficial to new functionalities such as rolling along walls.

Acknowledgements

The author would like to thank the FEDER and the European Union as well as the Region Midi-Pyrénées who supported the MIDLE project. The present study has been partially supported by the French DGA (MRIS) and Toulouse Tech Transfer. The author is grateful to the different students and coworkers who heavily contributed to the present work over the past years at ISAE: Boris Bataillé, Dominique Bernard, François Defaÿ, Jan Bolting, Maxime Itasse, Jacques Lamaison, Christian Colongo, Nicolas Quendez, Chinnapat Thipyopas, Murat Bronz, Manuel Reyes, Roger Barènes and Sergej Shkarayev.

References

- Bataille, B., Moschetta, J.M., Poinot, D., Berard, C. and Piquereau, A. (2009) 'Development of a VTOL mini UAV for multi-tasking missions', *The Aeronautical Journal*, Vol. 113, No. 1140, pp.87–98.
- Blanc, R., Vallart, J.B., Bataille, B. and Moschetta, J.M. (2008) 'Thick airfoils for low Reynolds applications: improvement of a biplane micro aerial vehicle', *European Micro Air Vehicle Conference and Flight Competition (EMAV 2008)*, July 8–10, Braunschweig, Germany.
- Bronz, M., Hattenberger, G. and Moschetta, J.M. (2013) 'Development of a long endurance mini-UAV: eternity', *International Micro Air Vehicle Conference and Flight Competition (IMAV 2013)*, 17–21 September, Toulouse, France.
- Bronz, M., Moschetta, J.M., Brisset, P. (2010) 'Flying autonomously to Corsica: a long endurance mini-UAV system', *International Micro Air Vehicle Conference and Flight Competition (IMAV 2010)*, July 6–8, Braunschweig, Germany.
- Bronz, M., Moschetta, J.M., Brisset, P. and Gorraz, M. (2009) 'Towards a long endurance MAV', *International Journal of Micro Air Vehicles*, Vol. 1, No. 4, pp.259–272.
- Carmichael, B.H. (1981) *Low Reynolds Number Airfoil Survey*, Vol. 1, NASA-CR-165803.
- Hammons, C. and Thompson, D.S. (2006) 'A numerical investigation of novel planforms for micro UAVs', AIAA Paper 2006-1265, *44th AIAA Aerospace Sciences Meeting and Exhibit*, 9–12 January, Reno, Nevada, USA.
- Holsten, J., Ostermann, T. and Moormann D. (2011) 'Design and wind tunnel tests of a tiltwing UAV', *CEAS Aeronautical Journal*, Vol. 2, Nos. 1–4, pp.69–79.
- Huo, C., Barènes, R. and Gressier, J. (2011) 'Numerical study on parametrical design of long shrouded contra-rotating propulsion system in hovering', *International Conference on Mechanical and Aerospace Engineering 2011 – ICMAE 2011*, 28–30 November, Venice, Italy.
- Itasse, M., Moschetta, J.M., Ameho, Y. and Carr, R. (2011) 'Equilibrium transition study for a hybrid MAV', *International Journal of Micro Air Vehicles*, Vol. 3, No. 4, pp.229–245.
- Laitone, P.B.S. (1978) 'Ideal tail load for minimum aircraft drag', *Journal of Aircraft*, Vol. 15, No. 3, pp.190–192.
- Lissaman, P.B.S. (1983) 'Low Reynolds-number airfoils', *Annual Review of Fluid Mechanics*, Vol. 15, pp.223–239.
- Loxton, B., Abdulrahim, M. and Watkins, S. (2008) 'An investigation of fixed and rotary wing MAV flight in replicated atmospheric turbulence', *46th AIAA Aerospace Sciences Meeting and Exhibit*, 7–10 January, Reno, NV, USA.
- McMasters, J.H. and Henderson, M.L. (1980) 'Low speed single element airfoil synthesis', *Technical Soaring*, Vol. 6, No. 2, pp.1–21.
- Moschetta, J.M. and Thipyopas, C. (2007) 'Aerodynamic performance of a biplane micro air vehicle', *Journal of Aircraft*, Vol. 44, No. 1, pp.291–299.
- Selig, M. and Guglielmo, J.J. (1997) 'High-lift low Reynolds number airfoil design', *Journal of Aircraft*, Vol. 34, No. 1, pp.72–79.
- Sher, I., Levinzon-Sher, D. and Sher, E. (2009) 'Miniaturization limitations of HCCI internal combustion engines', *Applied Thermal Engineering*, Vol. 29, Nos. 2–3, pp.400–411.
- Shkarayev, S., Bataille, B. and Moschetta, J.M. (2008) 'Aerodynamic design of micro air vehicles for vertical flight', *Journal of Aircraft*, Vol. 45, No. 5, pp.1715–1724.
- Shyy, W. (2008) *Aerodynamics of Low Reynolds Number Flyers*, p.34, Cambridge University Press, Cambridge, UK.
- Steenbakker, E., Barenès, R. and Lamaison, J. (2008) 'Design of an autonomous 18-cm ducted counter-rotating propeller VTOL MAV', *International Powered Lift Conference (IPLC 2008)*, 22–24 July, London.
- Stone, R.H. (2008) 'Aerodynamic modeling of the wing-propeller interaction for a tail-sitter unmanned air vehicle', *Journal of Aircraft*, Vol. 45, No. 1, pp.198–210.
- Thipyopas, C. and Moschetta, J.M. (2009) 'A fixed-wing biplane MAV for low speed missions', *International Journal of Micro Air Vehicles*, Vol. 1, No. 1, pp.13–33.
- Thipyopas, C., Barenès, R. and Moschetta, J.M. (2008) 'aerodynamic analysis of a multi-mission short-shrouded coaxial UAV: Part I – hovering flight', *26th AIAA Applied Aerodynamic Conference*, 18–21 August, AIAA Paper 2008-6243, Honolulu, Hawaii, USA.
- Thipyopas, C., Bataille, B. and Moschetta, J.M. (2007) 'Experimental investigations of biplane bimotor fixed-wing micro air vehicles', *3rd US-European Competition and Workshop on Micro Air Vehicle Systems (MAV07) & European Micro Air Vehicle Conference and Flight Competition (EMAV2007)*, 17–21 September, Toulouse, France.

- Thipyopas, C., Poutriquet, S., Barenès, R. and Moschetta, J.M. (2010) 'Aerodynamic analysis of a multi-mission short-shrouded coaxial UAV: Part II – translation flight', *48th AIAA Aerospace Sciences Meeting*, 4–7 January, AIAA Paper 2010-1427, Orlando, Florida, USA.
- Torres, G.E. and Mueller, T.J. (2004) 'Low aspect ratio wing aerodynamics at low Reynolds numbers', *AIAA Journal*, Vol. 42, No. 5, pp.865–873.
- Viieru, D., Albertani, R., Shyy, W. and Ifju, P.G. (2005) 'Effect of tip vortex on wing aerodynamics of micro air vehicles', *Journal of Aircraft*, Vol. 42, No. 6, pp.1530–1536.
- Watkins, S., Ravi, S. and Loxton, B. (2009) 'The effect of turbulence on the aerodynamics of low Reynolds number wings', *Engineering Letters*, Vol. 18, No. 3, EL_18_3_09.