TOOLS FOR FLIGHT DYNAMICS ANALYSIS IN THE DESIGN OF MAVS

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Abstract

A comprehensive review of micro aerial vehicles design and flight dynamics assessment will be carried out and followed by reporting the research activity of Politecnico di Torino concerning the MicroHawk platform. The configuration layout solution adopted will be discussed within the context of the preliminary design and the development phases of the micro aerial platform. The attention will then be focused on the flight dynamics issues, highlighting the attempt to produce a systematic correlation between aircraft dynamic response and MAV flying and handling qualities. The capability to establish a correlation between the above mentioned quantitative results and the qualitative ratings obtained from flight testing activity will be discussed. Finally, the results of a flight simulation implementation dedicated to investigate the dynamic behaviour of the MAV within its operating environment will be summarized.

1 Introduction

Micro aerial vehicles are object of considerable interest and development over the last years. A large number of successful MAV designs has been generated for either research or commercial purposes by several universities, industries, and government-funded institutions. Even if the majority of current vehicle concepts rely on fixed wings [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13], it is possible that MAV designs of the future will be based on rotary [8, 14, 15, 16] or flapping [17, 18, 19, 20] configurations in order to perform missions that require extreme agility, such as flight within a limited indoor area with obstacles and even reverse motion. Even if they are not able to perform hovering flight and they generally have relatively high stall speeds, fixed wing configurations provide a wider application because of their larger payload capabilities, the flight performances, such as mission range and endurance, and their ability to better withstand adverse weather conditions, with respect to flapping and rotary wings. Furthermore, fixed wing propeller-driven MAVs can be considered as miniaturized aircraft so that conventional design issues and procedures can be extended to this family of aerial vehicles.

A short review of the recent developments concerning this last category of MAVs is presented. The attention is focused on configurations, highlighting the different performances and the design approaches applied in the most successful projects of the last decade (see Tab. 1). The considered designs are characterized by 150 $\div$ 600 mm wingspan, low aspect ratio wings (AR = 1 $\div$ 2) and low Reynolds numbers flight regimes (Re = 75000 $\div$ 300000). The reference data also confirm that the existing fixed wing MAVs fly within a given range for weight and Reynolds number typical of birds and model airplanes [21], well below the regimes of conventional aircraft (see Fig. 1). Anyway, fixed wing MAVs exhibit stall and cruise speeds higher than those usually observed with recreational slowflyers. The analysis also suggests that higher dimensions imply an increase in weight with a limited reduction of wing loading (W/S = 20 ÷ 40 $\mathrm{N/m^2}$). As a consequence, taking into account the fact that these vehicles are penalized in terms of drag-polar and lift-to-drag ratio, higher endurance and climb performances are obtained by either increasing the weight fraction dedicated to energy storage or using an internal combustion engine.

The preliminary design phases of the above mentioned micro aerial vehicles are based both on analytical and experimental approaches. Due to their similarity with miniaturized aircraft, many researchers approach MAVs design by means of conventional tools for aerodynamics and flight performance prediction. One of the first and best known example is the Aerovironment Black Widow [1], a 150 mm wingspan fixed wing configuration, whose design started since 1996 with DARPA financial support. The activity covered aerodynamics, propulsion and energy storage sizing, stability and control analysis. These design issues were faced with lifting line theory, basic flight mechanics, wind tunnel testing of propulsive system and flight testing. The impact of configuration in terms of performances was assessed by implementing a multidisciplinary optimization procedure, involving aerodynamics, flight mechanics, structures and flight stability. The same design procedure was also implemented in several projects of other platforms, such as the 200 mm wingspan Trochoid [8] developed by MLB.

Many MAV-related aerodynamic studies were carried out based on wind tunnel testing, providing insight of the flow characteristics and a direct measurement of aerodynamic loads for airfoils and low aspect ratio wings. As to two-dimensional airfoil characterization, an extensive investigation was carried out at University of Illinois - Urbana Champaign by Prof. Selig [22]. Likewise, the University of Notre Dame started with low Reynolds numbers aerodynamics analysis and later focused on MAV related research. Two-dimensional airfoil characteristics were evaluated by analytical and experimental approaches [23], comparing quantitative and qualitative results and testing the reliability of classic instruments of aerodynamics analysis. Detailed studies of low aspect ratio wings at low Reynolds numbers [3, 2] were performed by means of wind tunnel experimental activities on wings of different planform shapes, in an attempt to single out the dependencies on the airfoil sections characteristics and to finally generate relationships applicable to practical MAV design. Flow visualization experiments were a valuable support to study the laminar separation bubble formation criteria and its influences on the overall performances. The activities on low Reynolds aerodynamics at University of Notre Dame were later directed to the design and development of a 235 mm wingspan fixed wing MAV whose propulsive system is based on an internal combustion engine and a tractor propeller [4].

The aerodynamic analysis, as a fundamental step of the design process, is still a critical phase of the MAV development, affecting flight performances, stability, maneuverability, and controllability aspects. The conventional tools exhibit a limited ability to estimate with accuracy low Reynolds number flows on low aspect ratio lifting surfaces [24], characterized by phenomena such as complex separation patterns, governed by relevant interactions between boundary layer development and vehicle geometry. Many researches faced with this problem by carrying out experimental wind tunnel testing on MAV models. An example is the Bidule MAV [9], a flying wing, 410 mm wingspan, powered by two electrical motors that has been developed by the University of Sydney. The wind tunnel testing activity was, actually, addressed to single out the effects of Reynolds number variations and the prop-wash effect on the aircraft aerodynamics and performances. Differently, the wind tunnel tests performed for the 150 mm wingspan micro aerial vehicle developed at the University of Florida, were addressed to evaluate the benefits of the flexible fixed wing with respect to a more conventional rigid structure; within this last project the wind tunnel results supported the flight tests and helped to evaluate the accuracy of CFD re-

♯	MAV	size (mm)	weight (N)	airspeed (m/s)	endurance (min)	propulsion (-)
1	Black Widow	150	0.6	11	30	DC motor
2	UND MAV	235	1	11	5	ICE
3	UF MAV	150	0.5	11	10	DC motor
4	Trochoid	200	1.5	15	20	ICE
5	Bidule	410				DC motor
6	Carolo	400	3.6	18	40	DC motor
7	Mirador	250	2	15	20	DC motor
8	MicroStar	150	1	15	20	DC motor
9	MicroHawk 150	150	0.35	$9 \div 15$	5	DC motor
10	MicroHawk 300	337	1	$7 \div 15$	10	DC motor
11	MicroHawk 600	600	4	$7 \div 15$	20	DC motor
12	MicroHawk 600	600	4	$7 \div 15$	60	ICE

Table 1 Characteristics of some propeller-driven fixed wing micro aerial vehicles.

sults [5, 6, 7]. The experimental activities also provided the aerodynamic database, on which the flight dynamics analysis [6] and the flight control system design of the vehicle [7] are based. Due to similar reasons, the definition of the reference aerodynamic database of CAROLO, a 400 mm wingspan microplane designed and developed by the University of Braunschweig for fully autonomous flight, was referred to wind tunnel readings [10] and was the basis for a nonlinear modeling of the aircraft dynamics.

From the analysis of available references on MAV design, it can be observed that, as a general rule, this last generation of aerial vehicles is designed and developed in terms of expected performances with a trial and error process, which is usually based on reiteration of flight experiments. Several aspects support this empirical approach, which is widely adopted by aeromodelers in the development of radio-controlled airplanes.

The design experience on these kind of vehicles is still limited and the definition of the reference aerodynamic database is not generally straightforward. Even if the vehicles are developed with the help of computational solvers [1, 8] or wind tunnel experiments [6, 7, 9, 10, 11, 12], part of the stability, damping and control derivatives can be only estimated by means of criteria based on past experiences on similar configurations [6, 7, 10, 11].

Flight dynamics analysis and preliminary control system design are discouraged by the inaccurate prediction of system dynamic response, affected by many model uncertainties (aerodynamics, propulsion system, actuator dynamics, ...). Differently from the large scale aircraft case, platform stabilization and loop closures (when available) are tuned with flight experiments during the development of the flying prototype.

As an additional remark, the development of flight simulation support for MAV design and remote pilot training is not so effective in terms of advantages for several specific reasons: low cost of prototypes, minimal environmental impact and limited flight test range requirements for line-of-sight remote piloting. Hence, not much of the resources scheduled for the project development is devoted for the assessment and the validation of either analytical or numerical accurate mathematical models of the vehicle.

As a consequence, the number of available references in the area of flight dynamics for micro aerial vehicles is quite limited. Flight dynamics modeling in MAV design has been approached by referring to linear state space models of the vehicle associated with typical trimmed level flight conditions, as presented in Ref. [7]. The simulation model was then used as the basis for the design of a measurement based nonlinear dynamic inversion control system and outer loop guidance system. As cited in Ref. [25], the wind tunnel data can be used to define a nonlinear model, then reduced to a level straight flight linearization equation. According to this equation, based on the idea of dynamic inversion, an attitude control law was devised and verified by nonlinear simulation. Later on, the 2-D guidance loop was designed. It includes the altitude control loop and heading control loop. Within the research presented in Ref. [10], the six DOF model of the microplane was represented by a set of nonlinear differential equations, taking into account highly nonlinear dynamic behavior, gyroscopic effects, actuator dynamics and turbulent atmosphere effects. This work was the basis for a further development towards the fully autonomous vehicle, consisting in the implementation of an autopilot [11].

The review of references suggests that a complete and comprehensive analysis of fixed wing micro aerial vehicles dynamics is not fully available yet. As a matter of fact, the attempt to produce a systematic correlation between aircraft dynamic response and MAV flying qualities is still under evolution. In any case, an accurate prediction of vehicle flying qualities would be extremely beneficial in minimizing the reiteration of flight experiments during the design process.

2 MicroHawk Configuration

MicroHawk concept was designed within a European Union funded project concerning Micro Aerial Vehicles for Multi Purpose Remote Monitoring and Sensing (MARVEL Project), by the Flight Mechanics group at the Aerospace Engineering Department of Politecnico di Torino. It consists of a fixed wing, tailless integrated wing-body configuration, powered by a DC motor and tractor propeller (see Fig. 2). The configuration has been fitted out with a circular section fuselage that locates propulsion system and payload. Two vertical fins have been added mainly due to lateral-directional stability requirements.

Three versions have been developed, characterized by different size and weight (Fig. 2), which fall within the reference range for gross weight and Reynolds number as shown by the empty symbols in Fig. 1. A 150 mm wingspan platform - named MicroHawk150 - has been designed and developed for very short range, remotely piloted missions, characterized by low flight duration and narrow operating scenario; this challenging design mainly demonstrated the flight feasibility in such dimension-speed flight regimes, according to the micro aerial vehicle DARPA definition. It has been equipped with basic on-board systems (DC motor, propeller, battery pack, controller, receiver and servos), for a total weight of approximately 35 grams. The medium-sized platform - named MicroHawk300 - is characterized by a 337 mm wingspan; as reported in Tab. 1, it weights about 100 grams in the unequipped version. The MicroHawk300 has been developed to perform a basic reconnaissance mission, carrying micro cameras and/or sensors for remote monitoring and sensing. The larger vehicle - named MicroHawk600 - is characterized by a 600 mm wingspan; the bare platform weights 300 g; its design has been mainly addressed to the need for higher payload weight fraction and larger internal volumes. Aerodynamics analysis was carried out by analytical methods and by experimental wind tunnel tests on a scaled model of the configuration. The aerodynamic database definition was the first approach to flight performance, stability and control studies [27]. Flying prototypes of MicroHawk150, MicroHawk300, and MicroHawk600 were equipped with off-the-shelf components, in an attempt to carry out a broad flight testing activity (see Fig. 3), as reported in Section 6.

3 Preliminary Design

Aeromechanic characteristics of the configuration were deeply analyzed before performing any experimental flight test activity. The main problems concerning the Micro Aerial Vehicle design were singled out and the attempt to solve them with a reasonably accurate but time-saving strategy was the objective of the MicroHawk preliminary design phase. The starting phase of the project consisted of relating 2D aerodynamics of aircraft wing section to aerodynamic characteristics of the 3D vehicle and evaluating its influences on flight performances; this challenging task was carried out by taking into account the low Reynolds number issues of the flow regimes of interest and by facing them both from analytical and numerical point of view [29].

As to the preliminary design of the Microhawk configuration, the analytical approach was based on three software modules, corresponding to the key aspects of the aircraft aeromechanic design:

- aerodynamics module: it deals with the estimation of aerodynamic characteristics of the airplane and with the evaluation of its stability derivatives and aerodynamic control parameters; the basic extended lifting line theory [30] was modified in order to predict the aerodynamic characteristics for low aspect ratio wings in the non-linear lift variation field, before reaching the stall condition [31];

- propulsion initial sizing module: it provides engine and energy source requirements, according to the aircraft aerodynamic characteristics;

- performance module: it evaluates the flight performances (range and endurance) of the aircraft, according to the characteristics obtained by the previous two modules.

The 3D experimental data, provided by wind tunnel testing within the Politecnico di Torino facilities, were compared with the results obtained using the extended lifting line theory, demonstrating good agreement in terms of aerodynamic forces and moments, in the flow regimes investigated. As a result, the reference aerodynamic database was defined by mixing experimental data (static coefficients, α and β derivatives, and control derivatives) and analytical results (damping derivatives); the aerodynamic database was used within the flight dynamics modelling and the flight simulation of the MAV platform.

Flight performance evaluation of MAV prototypes was computed by means of a software code in order to obtain the relationship between operational speed and required power and thrust. In-flight thrust and power requirements were estimated by conventional flight mechanics relationships, after vehicle drag polar estimation. Minimum flight speed and cruise speed (depending upon wing loading) were also estimated. The sizing of energy sources represented a challenging goal due to narrow constraints in terms of weight and required power; nevertheless, a feasible solution was found within the existing commercial market.

4 Mathematical Model

The mathematical model developed for off-line dynamics analysis and real-time flight simulation is a nonlinear representation of single engine aircraft with rigid fuselage (see Fig. 4). No small angle assumption is invoked for aerodynamic angles of the vehicle and the aerodynamics of fuselage and stabilizers is modeled using static coefficients and stability derivatives obtained by wind tunnel experiments at different angles of attack and sideslip angles. The effects of aerodynamic controls (elevator, aileron and rudder) are superimposed in terms of increments. The rigid body motion of the aircraft is modeled using six nonlinear force and moment equations and three kinematic relations (Euler equations). The most important feature of these equations of motion is that the states need not to be small quantities; thus, all the kinematic nonlinearities associated with the motion of the rigid body are retained.

The order of the complete system is 9 and the state vector can be represented as $\bar{x} = [u\, v\, w\, p\, q\, r\, \theta\, \phi\, \psi]^T$, while the control vector is defined as $\bar{u} = [\delta_e\, \delta_a\, \delta_r\, \tau]^T$. Since MicroHawk control is accomplished using two elevons, that can be actuated symmetrically and antisymmetrically, and no aerodynamic control surfaces are provided on the two vertical fins, a reduced control vector was considered in the MicroHawk mathematical modeling.

Referring to the MicroHawk design, a propulsive system model based on DC motor and propeller was implemented, including the mathematical correlation between supplying voltage and current drain with engine operating rpm and the relationships between propeller rpm and thrust and torque coefficients. The DC motor model is based on four parameters: stall torque, stall current, no load angular velocity and no load current. Propeller aerodynamics and performances are estimated by implementing the blade element theory, providing chord and twist distribution, together with 2D blade airfoil aerodynamics. Thrust and torque characteristics are evaluated according to flight conditions, throttle settings and aerodynamic angles.

The primary control actuators are also included in the mathematical model and their dynamic response is represented by a second order transfer function

$$\mathbf{G}(\mathbf{s}) = \frac{\omega^2}{s^2 + 2\zeta\omega s + \omega^2}$$

Concerning MicroHawk design, actuator's natural frequency and damping ratio were ω = 44 rad/s and ζ= 0.05.

The effects of atmospheric turbulence are optionally included in the present model. The gust linear and angular velocity components are generated step-by-step according to the power spectra provided by the theoretical model developed in Ref. [26], including the variation of turbulence scale and standard deviation of components with aircraft altitude and airspeed. The gust components are superimposed to the velocity components of the vehicle.

Initial values of altitude, airspeed, turn rate, sideslip and climb angles are given as inputs of the trim procedure, which is based on residual minimization. The algebraic equations enforcing force and moment equilibrium (9 eqns.) are combined with the additional kinematic equations (2 eqns.) that must be satisfied in steady flight or in a turn, and the combined system (11 eqns.) is solved simultaneously. The solution yields control and throttle settings, trim attitudes and rates of the entire aircraft.

The response to pilot inputs is obtained from direct numerical integration of the equations of motion, starting from trim conditions. The results here discussed were obtained by a 4th order Runge Kutta explicit integrator.

In an attempt to assess stability and control characteristics of the vehicle, a linearized set of small perturbation equations were extracted from the nonlinear model:

$$\dot{\bar{x}} = [A] \cdot \bar{x} + [B] \cdot \bar{u}$$

The coefficients of the state matrices $[A]$ and $[B]$ were derived numerically about the trim condition, using finite difference approximations. The linearization of the dynamic equations was carried out in the body fixed reference frame. The state-space representation was applied for evaluating flight dynamics characteristic modes (eigenvalues and eigenvectors characterization) and for estimating the frequency response of the system.

5 Flight Dynamics Analysis

The flying qualities and handling qualities requirements were introduced within the design procedure of MicroHawk platform, in order to test the compliance to conventional standards and to relate the dynamics analysis results to the qualitative ratings obtained by flight testing activity.

The addressed configuration was analyzed by implementing an off-line simulation based on the aircraft dynamics model, the propulsive system model, and the atmospheric turbulence model already described. The main aim of this work was to single out the flight dynamics characteristics of the reference layout, highlighting the effects of scaled dimensions, the aircraft behaviour in presence of atmospheric turbulence, the operating flight envelope extension and the effects of rotating masses (propeller) on flight performances. Therefore, the reference trim condition was characterized in terms of state variables, both with and without considering propeller effects. Due to the small deviation from level symmetric flight induced by the presence of propulsive system, the flight dynamics analysis was carried out by decoupling longitudinal and lateral-directional planes for the medium-sized and the larger versions, while it demonstrated the need for a further detailed investigation on the Micro-Hawk150 configuration.

The aircraft dynamics was based on eigenvalues and eigenvectors characterization; comparison to standard requirements demonstrated the applicability of flying qualities criteria and the satisfactory compliance to the reference values. Otherwise, some specifications showed to be higher than conventionally occurs, although they met the standard limits. Therefore, relationship between these characteristics and the frequency and time domain response was singled out.

Frequency domain response in the longitudinal plane indicated a conventional aircraft response and justify the analysis of control anticipation parameter boundaries applied to the platform. The high short period frequency was responsible of a worse handling qualities rating and was mainly related to the platform typical inertial characteristics. As expected, the behaviour dramatically deteriorated as the wing loading increases.

The bandwidth criterion was also applied and confirmed the previous result, by providing a very high bandwidth and a gain limited system.

Indicial response highlighted and confirmed the critical issues of the design and development, mainly related to the unconventional inertial and geometrical data and the high control surfaces effectiveness. The former item is unfortunately strictly related to the configuration and not modifiable considering the sizes, weights and center of gravity constraints. On the other hand, later flight tests pointed out the nervous response of the aircraft to the commands and led to a need for limitation of the control surfaces authority.

As a result of the open loop dynamics analysis, the need for flying qualities assessment was made evident and it was the basis for a further research development, aimed to the design of a flight control system addressed to the stable closure of the aircraft dynamics loop. Firstly, in an attempt to provide a solution for aircraft controllability, a lag compensator was introduced and it demonstrated the feasibility of a system dynamics improvement. Therefore, a more detailed flight control system design activity was started; as to the gain synthesis methodology, eigenstructure assignment and linear quadratic regulator techniques were evaluated in order to point out the most effective method for aircraft control. A roll damper was also designed in order to correct the degradation of lateral dynamic stability observed during experiments in pre-stall flight conditions. Finally, a technique for the inclusion of handling qualities requirements in the flight control system design process was tested. The search for an optimal controller in terms of handling qualities was performed numerically with a genetic algorithm [32].

6 Flight Testing

An extensive flight testing activity was carried out on several flying platforms, characterized by different dimensions (150 mm, 338 mm, 600 mm).

Three different structural solutions were identified for the flying version of the scaled prototypes: hot wire foam cutting of wings and fuselage, classical RC model lightweight wooden construction and kevlar/fiberglass forming in a mould (see Fig. 5). Light and very robust models were obtained using a lightweight wooden structure covered with thermally retractable mylar tape, providing a good surface finishing. Foam prototypes were found to be easier to produce by means of hot wire cutting, slightly heavier than the wooden ones but substantially prone to be crashed during accidental landing. Kevlar/fiberglass models, further heavier, showed to be very stiff and resistant to damage. They reproduced very accurately the reference geometry of the mould (manufactured by CNC at Politecnico di Torino in light stable hard plastics after CAD prototyping) and their surface can be coated with chemical color during forming. In the case of kevlar/fiberglass models, internal components were kept into position by a lightweight styrene foam mask, which also provided resistance to compression of wings and fuselage.

The first set of flight tests was performed with glider versions of the MicroHawk configuration, released from a carrier consisting of a RC trainer used to carry the model to a minimum altitude of 100 m (Fig. 6). These experiments had the scope to verify trim settings (tuning of static margin) and control stick deflection limits. Stability of flight and maneuverability were also verified after drop tests with and without propulsion system.

The second set of tests was addressed to the propelled version of the MicroHawk platform, and was devoted to set up the following items: hand launched/catapult take off, Li-Poly battery sizing for climb rate and endurance, DC motor cooling, model crash survivability, control surface dimensions, remote control regulations (stick authority), RC transmission range testing, optimal wiring of onboard electronics. A consistent number of flights was also spent to assess acceptable in-flight handling qualities and to achieve adequate remote pilot training, even in windy conditions.

As to the MicroHawk300 platform, good climb rates were obtained using 3-cells (Li-Poly 350 mAh - 9 grams). A power rate limiter was used after hand launch and initial climb for the 3-cells version to prevent DC motor damage.

Stable flight was obtained for the MicroHawk300 in the range from 6.5 m/s to 15 m/s with air vehicle weight ranging between 95 grams and 145 grams. Visual range for remote flight control was extended up to 250 m for an expert pilot. Endurance testing demonstrated that the platform can operate for 10 minutes.

Symmetric controllable stall was induced with progressive stick pull and recover was obtained with opposite forward stick control without lateral divergence. Pre-stall was marked by moderate roll oscillations.

Wind tunnel experiments on a gyroscopic rig were used to reproduce the effect of a roll damper in terms of lateral stick response and roll maneuverability. In-flight tests on a different flying demonstrator with equivalent characteristics showed that the feedback on ailerons was beneficial in terms of platform roll stabilization.

As previously mentioned, different wing loadings were adopted to verify the ability of the platform to perform the take off with a payload.

As a payload demonstrator, video downlink was tested using a commercial color CMOS videocamera with a 2.4 Ghz transmitter. In-flight good digital streaming was obtained up to 300 m range. Flight experiments were also carried out in presence of wind speeds up to 15 kts, in order to verify the stability/controllability of the platform in limit conditions (Fig. 7, Fig. 8).

The third set of experiments was related to the flight testing of the MicroHawk150. This scaled version was realized (2 prototypes were tested) with a lightwood structure covered with mylar tape (Fig. 9). The weight of the complete airframe without payload was below 35 grams.

The flight performances of the smaller MicroHawk platform showed to be very similar to those observed for the larger flying models.

The major problems encountered were:

- difficult tracking of model attitude: pitch and roll can be hardly detected by the pilot when the model is flying at distance (greater than 25 m);

- off-the shelf components are only partially adequate for an outdoor flying vehicle: servo-actuators are designed for indoor hinge loads with low precision elevatoraileron deflection; the receivers which fall in the very low weight RC model category are not designed to operate outdoor.

Nevertheless, propulsion system (propeller-DC motor-batteries) performed within the expected range, with sufficient excess power to handle the model in-flight after hand launch.

Trajectory control was accurate as a result of platform stability and controllability and several repeatable straight/turning flights were obtained.

7 Flight Simulation

As above mentioned, a wide activity of real-time flight simulation was carried out to support and validate the flight dynamics theoretical analysis.

The real-time dynamics analysis was based on Hexagon, a flight simulation software tool developed at Politecnico di Torino by the Aerospace Engineering Dept. and the Computer Science Dept. (for the rendering engine and graphical user interface development), addressed to the interaction of a user-defined aircraft mathematical model, a virtual instruments panel and a real-time data analysis graphic interface, flying the aircraft within a virtual scenario. The insertion of the aircraft model within a visual environment represent an added value from the flight analysis point of view. The Hexagon tool allowed a realistic recreation of the flying environment and related constraints (such as the flight in narrow places, see Fig. 10), reducing the - even though minor in case of micro aerial vehicles - risks of flight testing.

A graphical interface, dedicated to simulation session configuration, allowed to set the aircraft mathematical model (based on linear or non-linear formulation), the presence of atmospheric turbulence and/or the presence of winds, the starting flight conditions (in terms of flight speed, operating altitude, climb angle, steady turn rate) and the aircraft initial position with respect to an inertial reference frame defined by the scenario designers.

The Hexagon system also provided a virtual basic instrumentation panel, consisting of anemometer, altimeter, variometer, artificial horizon, turn coordinator, analog indicators of aerodynamic control surfaces deflection and battery charge indicator. Although not usually provided in a MAV ground control station, the virtual cockpit was considered to provide and improvement in flight analysis capability, by correlating qualitative information from visual flight with quantitative data reported in a cockpit-like form.

The real-time data analysis interface represented a key approach to the flight analysis, by providing information concerning the main flight parameters trend during the simulation session running. Therefore, it was possible to quantitatively evaluate the aircraft response to maneuver, the stall behaviour, the dynamic stability characteristics and the control surfaces effectiveness. The graphical interface also allowed to save simulation data on file for a post-simulation session analysis.

The real-time flight simulation activity was based on several set of simulation running, intended to evaluate:

- MicroHawk flight performances and capability to perform a standard mission profile;
- suitability of propulsive system sizing as a validation of preliminary design choices;
- effects of propeller on aircraft maneuverability, in terms of torque, aerodynamic loads due to non axial flow on the actuator disk, and gyroscopic moments;
- flight dynamics characterization, as to aircraft dynamic modes estimation (eigenvalues, eigenvectors, damping and natural frequency);
- scalability effects, intended to evaluate differences in aircraft behaviour due to configuration sizes and weights.

The reference starting condition of the reported simulation testing was a straight level flight, characterized by 10 m/s speed at 100 m S.L. operating altitude. No atmospheric turbulence nor winds effects were considered.

8 Concluding Remarks

The design of Micro Aerial Vehicles is a tricky problem, considering the research activities involved in different disciplines, ranging from fluid dynamics to flight dynamics, from structure to on board systems, from flight control systems to communications, in an extremely reduced scale. Probably the development of the nanotechnologies in the near future will consistently help the scientists and the engineers to make progresses in this field. The activity described, supported by the European Union, in the IST Thematic Area of the Future and Emerging Technologies Programme, was an opportunity to investigate many focal items in the design of MAVs and was also a unique experience of systems integration in demanding conditions in terms of weight and dimension. The prototype developed involved activities in low Reynolds aerodynamics, configuration optimization, mathematical modelling, flight dynamics analysis and flight testing. In particular, flight dynamics studies, including the analysis of flying qualities and handling qualities, were an opportunity to extend the traditional theories to a novel concept of aircraft. The design of a flight simulator able to host the MicroHawk mathematical model permitted to perform a real-time dynamic analysis, to verify flying and handling qualities for the different prototypes, and to define suitable mission profiles. This was a unique tool for evaluating the aircraft scale effects from the aeromechanics point of view. Flight tests confirmed the qualities and the shortcomings for the three prototypes studied and manufactured. The activity is going on and a flight control system is under test on MH600, in order to perform autonomous flight.

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Nomenclature

ICE	Internal Combustion Engine
p,q,r	Angular velocity components (body axes)
s	Complex variable (Laplace transform)
S	Wing area
u,v,w	Velocity components (body axes)
$\bar{u}$	Control vector
$\bar{x}$	State vector
α	Angle of attack
δ_a	Aileron stick control
δ_e	Elevator stick control
φ, θ, ψ	Angles of roll, pitch and yaw (Euler angles)
ζ	Damping ratio
ω	Frequency

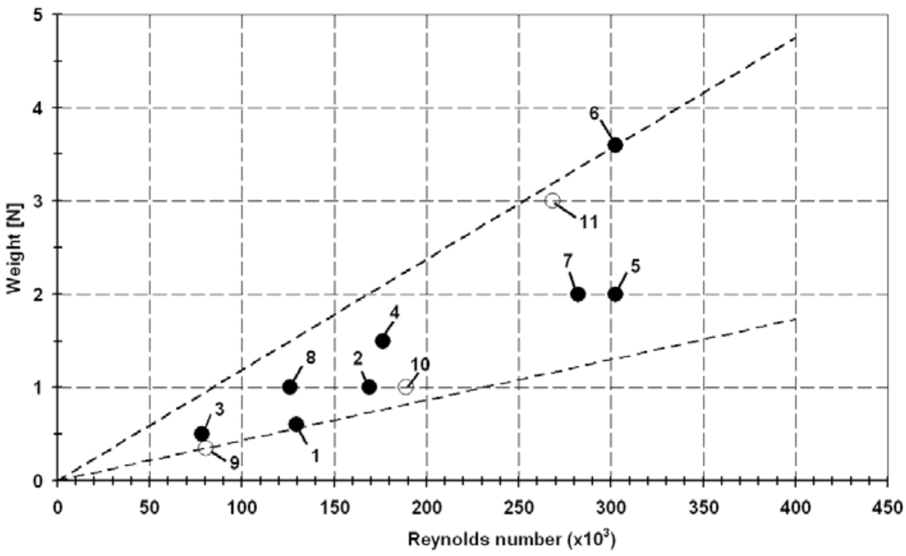

Fig. 1 Gross weight and flight Reynolds number comparison for several MAV configurations (see Tab. 1).

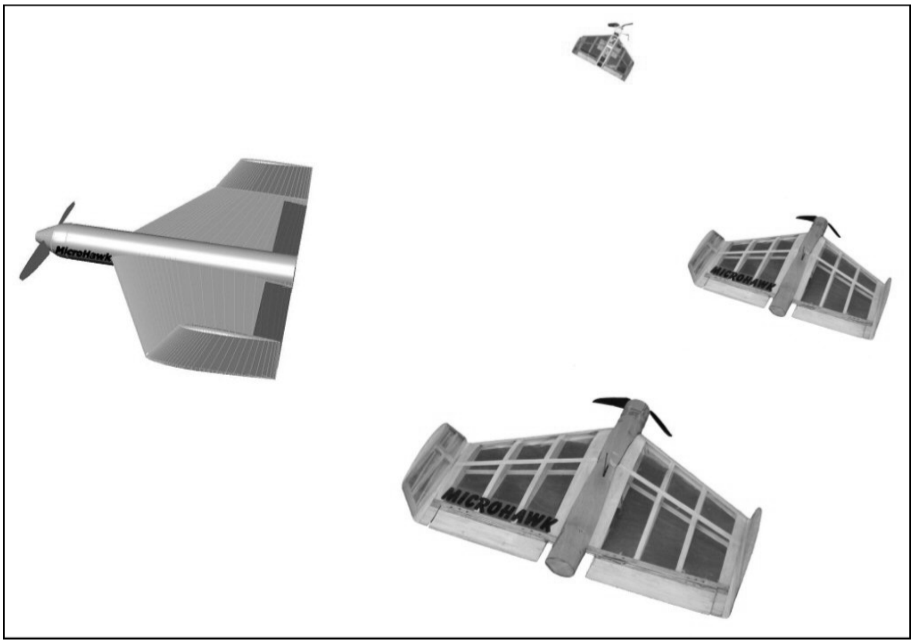

Fig. 2 The micro aerial vehicle configuration (MicroHawk) and the existing scaled versions.

Fig. 3 The micro aerial vehicle during the flight test activity.

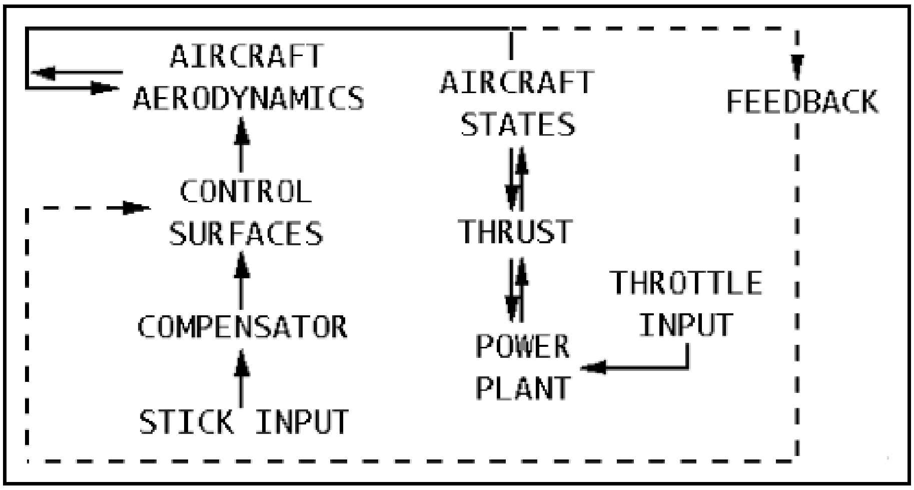

Fig. 4 The mathematical model implemented within the off-line flight dynamics software code and the real-time flight simulation tool.

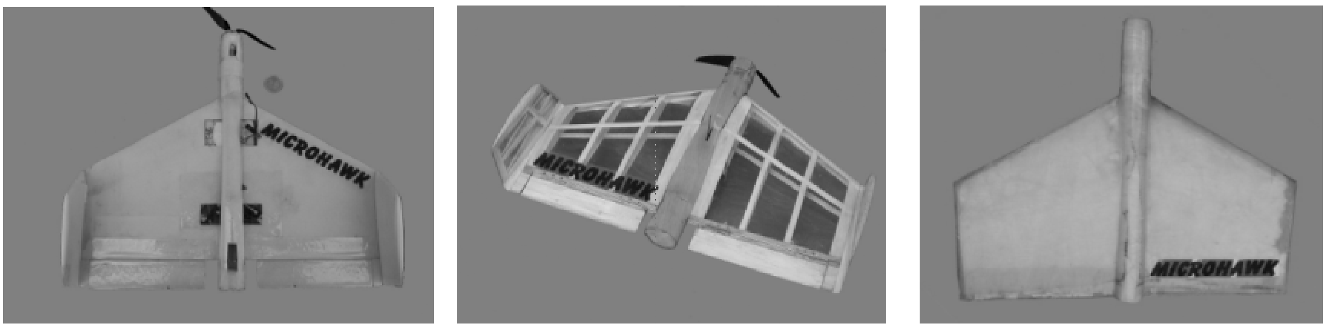

Fig. 5 Different structural solutions for flight testing of the scaled prototypes.

Fig. 6 MicroHawk prototype for gliding flight.

Fig. 7 Video camera positioning within the MH300.

Fig. 8 Camera view from MH300 during flight.

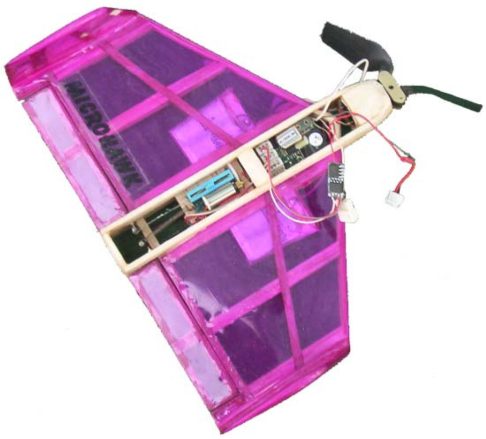

Fig. 9 MH150 flying prototype.

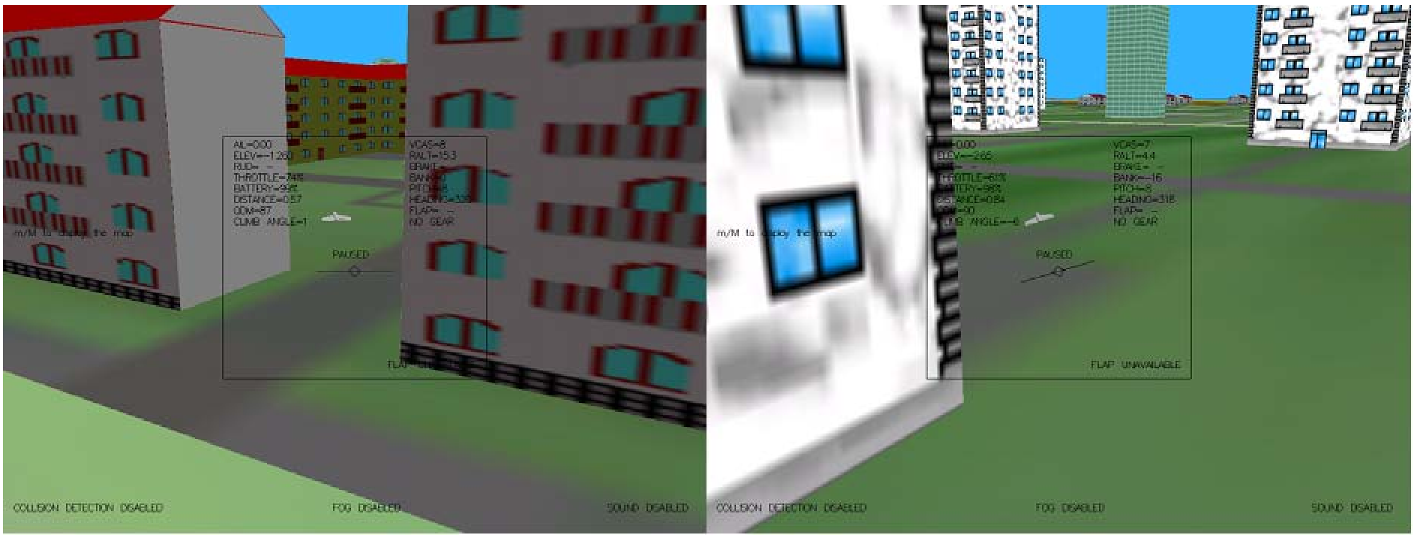

Fig. 10 Flight simulation environment.