UAVs and simulation: an experience on MAVs

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Abstract
Purpose – The purpose of this paper is to report the research activity of Politecnico di Torino concerning the MicroHawk platform (micro-aerial vehicles – MAVs) and to present the design and the development of a basic flight simulator for educational/training purpose.
Design/methodology/approach – A simulator is an easy-to-use system for the analysis of maneuver response, the dynamic study and the evaluation of the aircraft flying and handling qualities for different aircraft categories. The software implementation, including the definition of mathematical model, the visual scenario and the real-time data analysis graphic interface, are delineated in this paper. In addition to this experimental phase, an important effort is done to incorporate simulation into the autopilot tuning process.
Findings – An intense flight activity is carried out to test the flight control system performances of the MicroHawk platform and to establish general procedures to ensure the correct operation of all subsystems. The automatic flight of MAVs has been studied with success for territorial surveillance and map project.
Research limitations/implications – In order to simplify the use of these platforms by the end-user, a software interface will be designed to calculate automatically the flight plan, ensuring the desired trajectory design and collision avoidance.
Originality/value – The autopilot simulation integrated with vehicle's dynamics can be used to reduce the platform set-up time and the risk of losing the prototype. The simulator training permits to study flight complex plane, in order to obtain better platform performances in real conditions. Starting from a simple scenario, it is possible to set up and upgrade the mission at any time during the simulation.

Keywords Flight, Simulation, Control systems, Training methods, Aircraft navigation

Paper type Research paper

1. Introduction

In the last decade, the term micro-aerial vehicles (MAVs) has been used to define flying objects characterized by reduced physical sizes and can be thought of as:

> [...] aerial robots, as six-degree-of-freedom machines whose mobility can deploy a useful micro payload to a remote or otherwise hazardous location where it may perform any of a variety of missions (Grasmeyer and Keennon, 2001).

A large number of successful MAV designs has been generated for either research or commercial purpose by universities, industries and research centres. The majority of current vehicle concepts rely on fixed wings, because they generally provide wider applications in terms of payload capabilities, flight performances, such as mission range and endurance, ability to better withstand adverse weather conditions (Figure 1).

Most of the research efforts are focused on providing them with automatic systems, since the nature of MAV missions and their duration, could create an unbearable workload or a decreased attention in remote human operators that would probably lead to deficient mission performance.

The preliminary design phases of the above-mentioned MAVs are based both on analytical and experimental approaches. Owing to their similarity with miniaturized aircraft, many researchers approach MAVs design means of conventional tools for aerodynamics and flight performance prediction. The activity covers aerodynamics, propulsion and energy storage sizing, stability and control analysis.

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 or wind tunnel experiments, part of the stability, damping and control derivatives can be only estimated by means of criteria based on past experiences on similar configurations.

The Aerospace Engineering Department of Politecnico di Torino is working on the development of the MicroHawk family of MAVs since some years. At the moment, one of the main goals of the research group is to achieve high-performance autonomous flight. To this aim, an intense flight activity is being carried out in order to test the flight control system (FCS) and, at the same time, different control design methods are being investigated to set the FCS parameters and achieve the desired specifications in terms of performance and robustness.

These kind of vehicles usually are designed and developed with a trial-and-error process through an intense flight activity, both for the relative low cost of prototypes and for the absence of human risk. Even so, final costs may be remarkable, since it is very time-consuming.

For this reason, incorporating simulation into the design process is useful to reduce the experimental phase, and consequently its costs. Clearly, to obtain satisfactory results it will be necessary to work with a mathematical model as close as possible to the real physical system.

2. The simulation platform

Traditionally, flight simulators are used during the design phase of an aircraft and for operator training, as well as for

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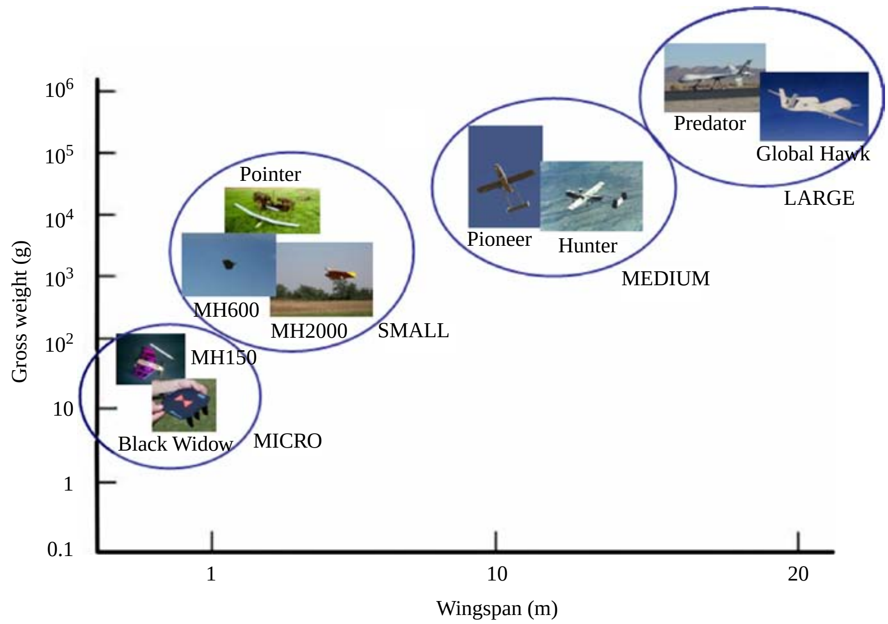
Figure 1 Flight regimes characteristics of different classes of air vehicles



entertainment applications. The latter field of application, widely known from many years, provides graphically advanced commercial products, focusing on the level of realism of the rendered scene and the simulation real-flight procedures (pre-flight briefing, ATC communications, navigational flight, and so on), so much that an interest in crew training applications has been also demonstrated. Moreover, many interesting works can be encountered for within the research field, where high-realism level of virtual environment is combined with highly accurate mathematical modeling, due to a profitable choice of inter-disciplinary. Particularly, one of the scope of the flight simulator is to provide users of an effective tool for the aircraft design as well as the understanding of the fundamentals of flight mechanics topics.

The progresses in computer science, in terms of reduction of systems complexity and costs, made possible the design and manufacturing of low-cost flight simulators, tailored for educational purposes. The essential requirements of those instruments are: easiness to use, the possibility to use general purpose hardware (PCs), low level of complexity for the visual scenario, high level of interaction with the user.

The design requirements of this simulator are consistently different from those ones of the traditional flight simulators: it is important to give to the operator the possibility to have a view in real time of the parameter trends and to have the possibility to re-examine later those trends.

2.1 Simulation platform architecture

The proposed architecture consists of a high-performance computer cluster connected by a Gigabit Ethernet bus, that handles the interactions among the mathematical model software, the scenario rendering engine and the graphical user interfaces.

The cluster of the HEXAGON™ Flight Simulator (Figure 2) consists of two personal computers, one dedicated to the mathematical model and to the rendering engine and the other for managing the LABVIEW™ applications. The graphics interface is demanded to the three LCD monitors: the central one to display the visual scenario environment, the right one to display the virtual cockpit and the third one to visualize real-time flight parameters Nevertheless, the position of the virtual cockpit and the time history analysis screens can be inverted according to the instinctive requirement of the user.

The operator interacts with the system by means of keyboard, 3D joystick, and rudder pedals.

The information related to aircraft configuration geometry, aerodynamic database, propulsion and systems characteristics are introduced by formatted files. These files are created using ACInterface™, a Java™-based software package.

Figure 2 The HEXAGON Flight Simulator hardware

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The main software packages are represented by the aircraft mathematical model and the scenario rendering formulation. The former one is developed in Fortran language and it consists of three sub-modules: the aircraft dynamics model, the propulsive system model and the atmospheric turbulence model. The rendering engine, developed in C/C++ programming language and based on OpenGL libraries (Shreiner *et al.*, 2003), performs the visualization of a comprehensive scenario by means of textured altitude maps and polygonally modelled buildings (Figure 3).

The need for a portable code, intended for general purpose hardware, implied the use of software available for different platforms and the implementation of a basic synthetic environment. The key aspects are the supplying of reference points within the virtual scene as an help for the user performing the simulated flight. A bare head-up-display is also provided, showing the main information regarding flight parameters in digital format.

The visual scenario environment also includes a 3D aircraft model. The rendering engine allows to set a camera view (internal or external) and a camera zoom. In the case of external view, the loaded 3D model is visible and the user can change its point of view, by rotating around the vehicle during the simulation session.

The mathematical model and the rendering engine interface themselves in the flight simulation environment by exchanging data and communicate with the user by means of three output devices. The first one is the synthetic environment, as mentioned above, collecting and visualizing the information related to the aircraft position and attitude. The second device is the virtual cockpit, consisting of a virtual instrument panel, realized in the LABVIEW environment (Figure 4).

The third output is a graphical interface for the real-time data analysis. It shares the LABVIEW environment with the cockpit, allowing the analysis of flight parameters trend

Figure 3 The educational flight simulator visual scenario: an external view of a MAV vehicle

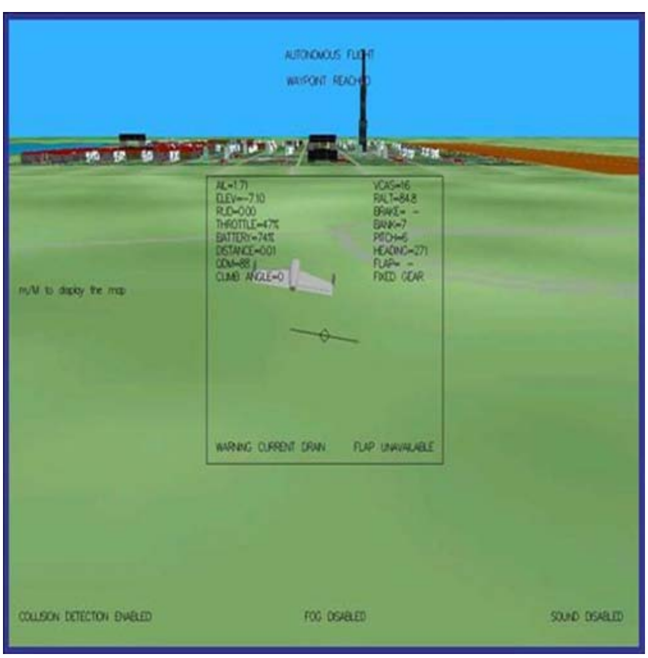

Figure 4 The virtual instrument panel

during the simulation. In addition off-line data processing can be performed as the output data can be saved in a formatted file.

3. Mathematical modeling

The Flight Simulator software code is based on high-fidelity mathematical models, representing the aircraft dynamics, the propulsive system, the atmospheric turbulence and Earth winds. As to the aircraft dynamics, a nonlinear set of equations of a 6 degrees of freedom motion is implemented (Gainer and Hoffmann, 1972). The common assumptions of the classic atmospheric flight mechanics theory are considered, without limitations in the observable aircraft model:

- rigid body: flexible modes characterizing the aircraft motion are neglected;
- stationary flat Earth: a reference frame fixed with the Earth is an inertial one;
- vehicle plane of symmetry: due to the presence of the *X-Z* plane in the body axes reference frame, remarkable simplification can be encountered for in the formulation of the equations of motion; and
- constant gravitational acceleration.

Within the aircraft model, six equations express the equilibrium of forces and moments acting along the body axes, accounting for the aerodynamic, propulsive, inertial and gravitational loads. Three non-linear differential equations (kinematic relations) represent the rates of the Euler angles, while three equations are used for the aircraft velocity components in a vertical local axes frame. The integration of the latter set of equations during the simulation process allow to obtain the aircraft position.

The most important feature of the implemented mathematical model is that the states need to be small quantities; thus, all the kinematic nonlinearities associated with the motion of the rigid body are retained.

The main limit of a model based on Euler angles method consists in the possible occurrence of a singularity for unconventional flight conditions. In order to avoid this singularities, if highly maneuverable aircraft flight has to be reproduced, a quaternion method is commonly applied.

It is based on four independent parameters to define the aircraft orientation: three to locate the direction of the rotation axis and the fourth one to represent the rotation angle.

Simulation sessions can be carried out in an ideally calm air or in presence of atmospheric gust and/or Earth winds. As to the former one, it has to be noted that the atmospheric turbulence is the major cause of disturbance of trajectory and flight attitude. The gust linear and angular velocity components are generated step-by-step according to the power spectra provided by the theoretical formulation, (US Department of Defence, 1997) including the variation of turbulence scale and standard deviation of components with aircraft altitude and airspeed (MAVTech s.r.l., 2006). The gust components are subtracted from the velocity components of the vehicle.

The winds influence the relative velocity of the aircraft and so affect its flight performances. They have to be defined in terms of intensity, elevation angle and direction. 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 response to pilot inputs is obtained from direct numerical integration of the equations of motion by a 4th order Runge-Kutta explicit integrator, starting from trim conditions.

4. Graphical user interfaces

The Flight Simulation tool provides main graphical user interfaces, partially for input simulation run data and partially for output maneuver response results.

The former one copes with ACInterface, a Java-based software package designed for the preliminary subsonic aerodynamic analysis of conventional and tailless aircraft. The data entry procedure allows to define the geometry, the propulsion system and the mass distribution of the configuration. The data for the configuration are saved and can be retrieved later for further analysis (Yeager, 1998).

The user has also the possibility to set the mathematical model (Bryan method for linear model and Tobak-Schiff method for non-linear model), to choose between Euler angle method and quaternions one; the user can also decide for the occurrence of gusts, by eventually setting type, starting time and duration, and the presence of winds by setting intensity, elevation angle and direction. The 3D model of the aircraft to be visualized in the scenario is also set by switching among the available files (in 3DS format) or by the user-defined files.

The optional collision detection for obstacles and the presence of turn points marked according to usual VFR flight references (runways, buildings, lakes, mountains, and so on) are introduced in the visual environment to drive the attention of the virtual pilot on aircraft trajectory control instead of medium range navigation.

The virtual cockpit gives an instrumental output for overall flight and trajectory control. The panel is the same for any aircraft as a prerequisite to compare different vehicles with any installed powerplant. As an aid for the aircraft response understanding and to provide a more complete data set of information, sliding indicators of control surfaces position and throttle control have been added.

Real-time data are displayed as running graphs so that the user can freeze in any moment the plots of flight parameters. An option for flight parameter storage is also provided and gives a fundamental help in understanding aircraft behaviour by correlating qualitative considerations and quantitative data in a post-simulation analysis procedure.

5. The MicroHawk project

The MicroHawk concept (Quagliotti and Guglieri, 2007) is designed within a European Union-funded project (MARVEL, MAVs for Multi Purpose Remote Monitoring and Sensing Project), by a research group at Politecnico di Torino. The MicroHawk configuration is characterized by a conventional layout: it is a fixed wing, tailless integrated wing-body configuration and tractor propeller driven.

The configuration has several advantages: the design is compact with an adequate aerodynamic efficiency, masses and subsystems are concentrated, structures are light and severe aeroelastic problems are rejected as no tailplane is present, stall is smooth and the configuration is spin resistant and stable in flight. Some disadvantages: high-lift devices are difficult to apply and the platform has a limited acceptable range for payload location due to stability margin constraints.

Different versions of the MicroHawk configuration exist, covering a range of dimensions and operating performances. The availability of different MicroHawk versions allows covering an extended range of flight speed (estimated between 7 and 20 m/s) and flight endurance (ranging between 15 and 60 min, according to size and energy source storage) (Table I).

The medium size vehicle – named MH600 – is characterized by a 600 mm wingspan. Its design is mainly addressed to the need for higher payload weight fraction and larger internal volumes. The MH600 version can achieve autonomous flight, as it is possible to locate on-board a commercial small size autopilot (Micropilot MP2028) without exceeding wing loading limitations for hand launch. The navigation system, based on inertial and GPS data are programmable according to tasks and waypoints.

A new research activity supported by Programma Nazionale di Ricerche in Antartide is expected to promote the application of innovative exploration techniques (such as autonomous flying vehicles) within the scientific activities performed by the Italian researchers in Antarctica. Within this area of interest a larger platform (MH2000 with a 2,000 mm wingspan) is under development. The basic concept is the aerial support to continental and maritime observation performed by means of an unmanned vehicle remotely controlled by an operator. A communication link with a ground control station based on satellites is also considered. The payload is hosted within the fuselage in a

Table I MicroHawk layout geometry

	MH600	MH2000
Wing		
Wingspan (m)	0.600	2.000
Aspect ratio (–)	1.875	1.915
Root chord (m)	0.400	1.333
Sweep (°)	30	30
Fuselage		
Length (m)	0.52	1.750
Width (m)	0.055	1.430

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modular section. The typical payload is a set of scientific instruments (i.e. magnetic field sensors) that will acquire data to be stored on-board during the flight. Different MH2000 versions (powered by a DC motor) will be shortly available for surveillance, one of them being equipped with micro-fuel cells. A version of the MH2000 platform will also be used for demonstrations (image detection) within the project Information Technology for Humanitarian Assistance and Cooperation Actions based on a Memorandum of Understanding signed between Politecnico di Torino and Word Food Program.

Several flight tests are carried out in order to evaluate stability and control characteristics of the MicroHawk configuration (Figures 5-7).

The typical mission profile can be described by the following phases:

- Take-off procedure can consist of hand launch or traditional take-off for MH2000.
- Whether autonomous or under remote piloting controls are enabled; the former solution should be the only one applicable in the case of out-of-sight flight, due to long mission ranges, higher operating altitude, inaccessible spots or lack of visibility.

Figure 5 MicroHawk in flight experiments (MH600 version)

Figure 6 The MicroHawk mission profile

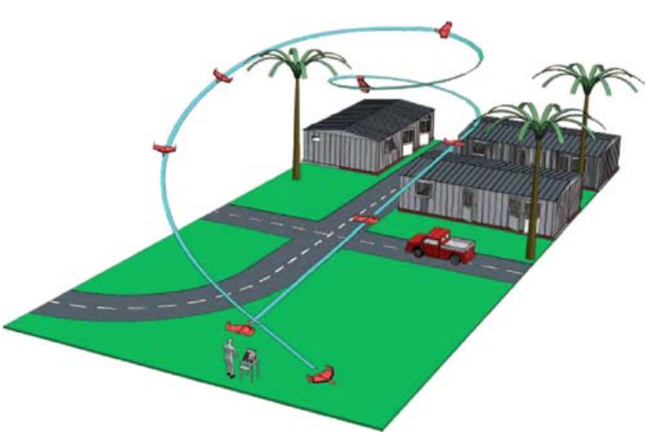
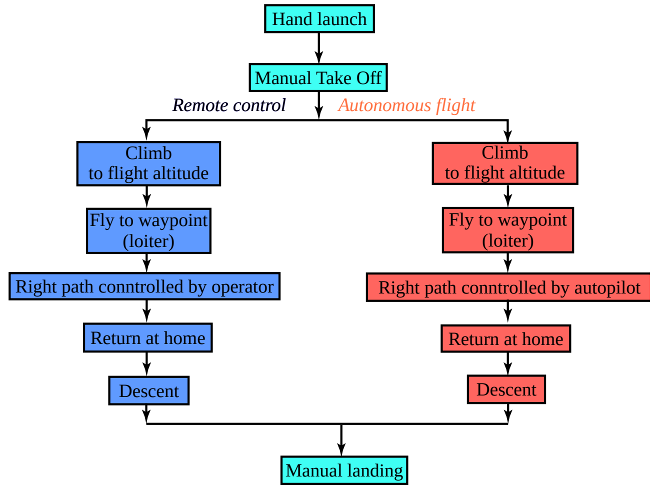


Figure 7 The MicroHawk mission sequence



- In-flight operations. The platform can take on-board a payload consisting of sensors or microcameras, depending on the mission profile, the geometric sizes and the required power.
- Landing procedure, both for autonomous and remote piloting control, is conventional-like, without system for assisted landing (i.e. parachute).

Flight test activity is also mandatory to explore the feasibility of practical applications in the real world. As a matter of fact, European civil aviation authorities have recently outlined (Guglieri *et al.*, 2006) the limits for in-flight operations of light unmanned aerial vehicle (UAV) systems. These restrictions must be clearly kept in mind when the platform should operate in urban areas and/or in presence of operators who could be potentially injured in case of accidental impact.

Taking into account the impossibility to execute flight tests, the operator can utilize the simulator as a relevant option to simulate the desired flight on HEXAGON.

The regulatory restrictions and their application to in-flight operations is a vital aspect. Their practical implications could preclude future development of MAVs. National aviation authorities have an evident role in this field.

6. Practical applications: autopilot tuning for MicroHawk600 and MicroHawk2000

In order to reduce the costs of a prototype and the experimental phase is useful to incorporate simulation into the design process.

During simulation and flight-testing phases, deficiencies in control design are invariably found, requiring correction in the controller. For this reason, flight control designs are usually based on several PID controllers, since it is "easy" to intelligently alter the parameters in order to achieve the closed-loop specifications. Considering that the process of testing the controller may be expensive and time-consuming, this ease helps reduce costs and set-up time.

The autopilot selected to equip MicroHawk is also based on PIDs. More specifically, the autopilot used is the commercial MicroPilot Autopilot MP2028g, which is a multi-loop PID autopilot designed for fully autonomous MAV operation.

Capabilities include airspeed hold, altitude hold, turn coordination, GPS waypoint navigation and autonomous launch and recovery. Its low weight of only 28 g makes it suitable for micro/mini-UAVs (Micropilot, Inc., 2007).

The MH600 platform is a multi-purpose mini-UAV based on the MicroHawk configuration, and it is characterized by a wingspan of 600 mm and a wing area of 0.192 m^2 (Figure 8). The first prototype equipped with autopilot has a mass of 620 g and it has a limited payload capacity of about 50 g. This wing-load constraint is mainly due to the fact that this platform must be launched manually.

Flying at an average speed of about 12.5 m/s, the current electric batteries provide a flight endurance of about 30 min. The MH2000 platform (Figure 9) is a multi-purpose mini-UAV based on the MicroHawk configuration, and it is characterized by a wingspan of 2,000 mm and a wing area of 2.140 m^2. The first prototype equipped with autopilot has a mass of 8.130 kg and it has a payload capacity of about 2 kg. The flight envelope of the MH2000 ranges from 10 to 33 m/s at sea level, and the platform is designed to fly up to a maximum altitude of 300 m from the launching point. Flying at an average speed of 15 m/s, the current electric batteries provide a flight endurance of about 40 min.

Figure 8 The MicroHawk platform

In order to be to perform a study on autopilot performance and as a contribute to HEXAGON development, some autopilot functions have been included into the code. The feedback loops implemented are enabled or disabled according to the flight mode (level flight, climb and descent).

The PID gains must be introduced in MP2028g units, so as to make easy the posterior setting into the autopilot. Furthermore, other PID features present on the MP2028g such as anti-windup limiting, smooth gain scheduling, output limiting, output slew rate limiting, and input limiting for each PID channel have also been incorporated.

So, this simulator helps understand the effects that each gain may have on platform dynamics and makes possible to perform an initial gain setting of the autopilot prior to going to the airfield. This procedure allows to reduce the platform set-up time and the risk of losing the prototype.

For the MH600 platform, it was decided to simulate a four-waypoint square circuit for autopilot tuning. The results are obtained for a target altitude of 80 m and a target speed of 15 m/s (Figures 10-12).

For the MH2000 platform, it was decided to simulate a four-waypoint rectangular circuit for autopilot tuning. The results are obtained for a target altitude of 120 m and a target speed of 15 m/s (Figures 13-15).

Figure 9 The MH2000 platform

Figure 10 Four-waypoint square circuit simulation

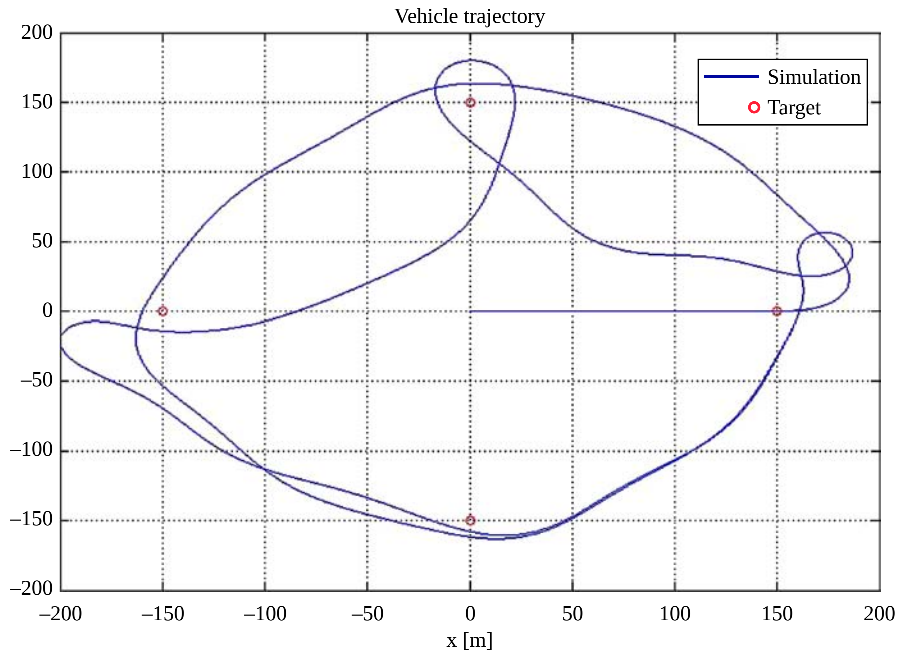
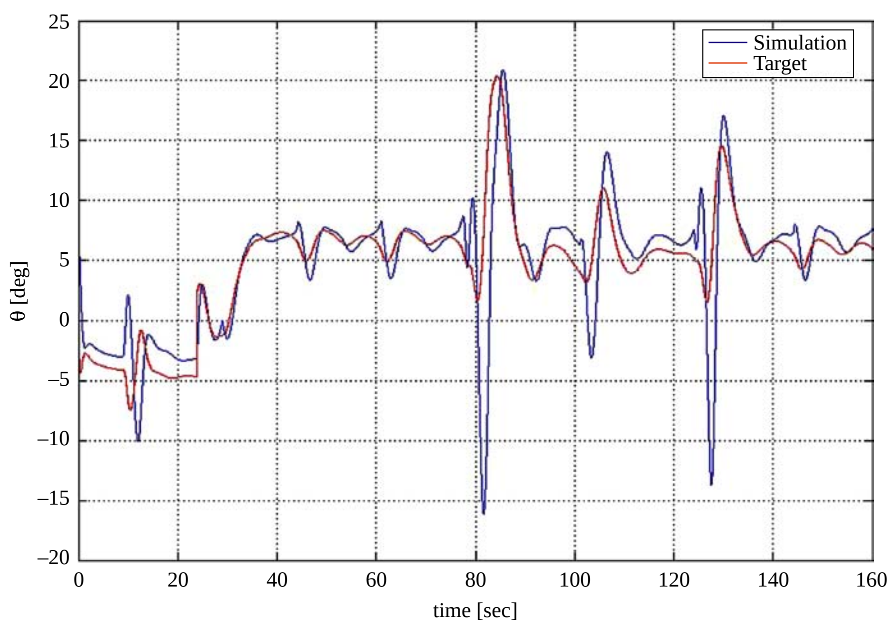


Figure 11 The pitch response for the MH600 platform



In the first seconds of simulation the autopilot executes a realignment loop due to the remodelling algorithm for the heading phase.

7. Pilot training

Flight simulation enables to learn aircraft performance, experience aerodynamic effects and perform flight maneuvers as closely and realistically as possible. The pilot can adjust different factors that affect flying, such as hazardous weather conditions, immediately and without the risk of losing the prototype. Using flight simulator, the operator is able to train for situations that are unsafe in the aircraft itself.

Because of the piloting complexity of MAVs, the operator with HEXAGON has the necessity to make the platform tuning both in the remote flight and in the autonomous one and to become confident with the platform. For this reason,

Figure 12 The roll response for the MH600 platform

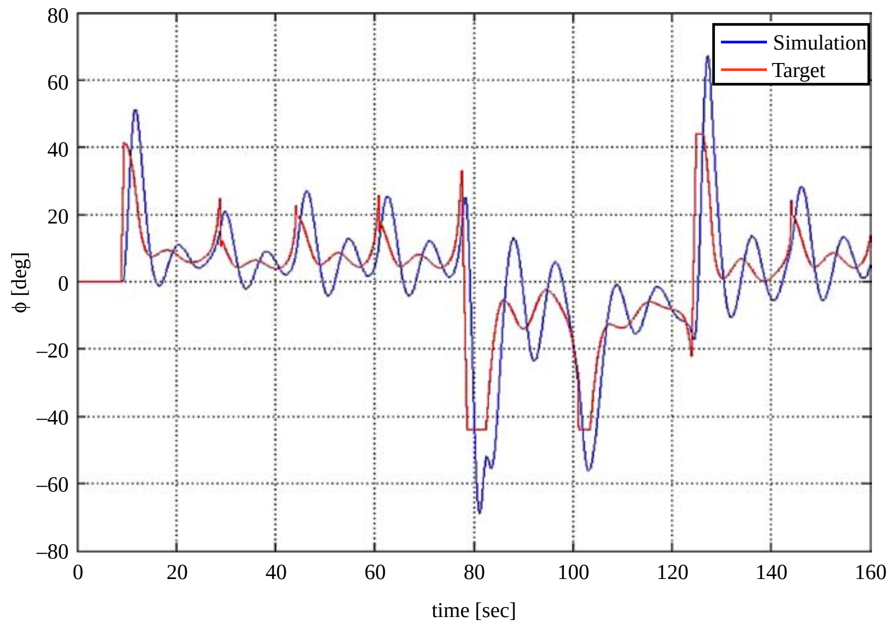
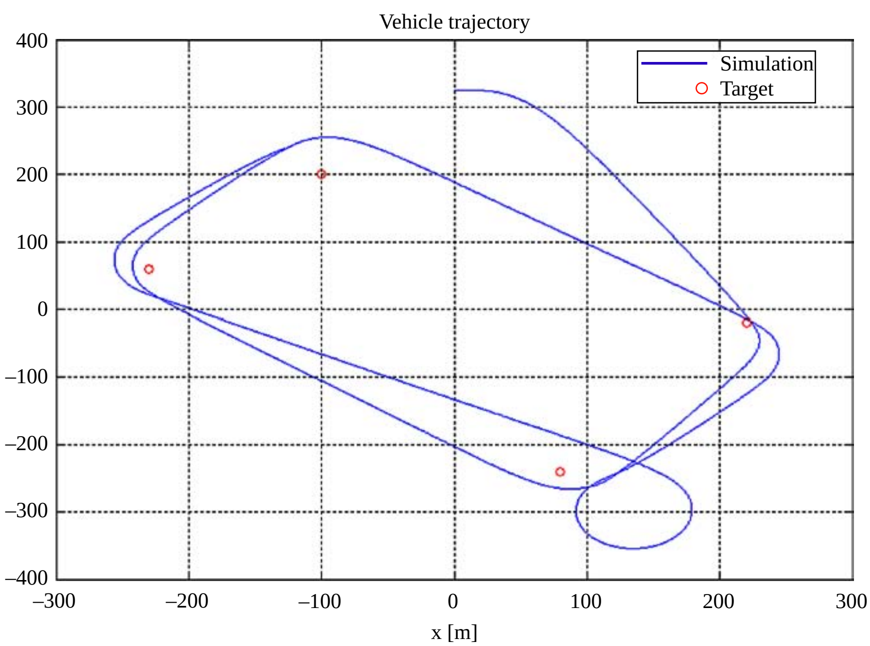


Figure 13 Four-waypoint rectangular circuit simulation



besides the use of joystick, the MicroHawk platform simulator can be piloted using a remote radio control. To fulfill this requirement, an interface radio control/simulator has been embedded on HEXAGON, to make more realistic the piloting of the platform.

Moreover, the simulator training permits to study flight complex plane with the MP2028 autopilot. The pilot can execute a preliminary analysis of autopilot parameters, such as the PID gains, in order to obtain better platform performances in real conditions. Starting from a simple scenario, it is possible to set up and upgrade the mission at any time during the simulation.

8. Flight test data

Although simulation significantly reduces the real flight testing, the final autopilot tuning must be performed at the airfield, since the behaviour of the system will never be exactly

Figure 14 The pitch response for the MH2000 platform

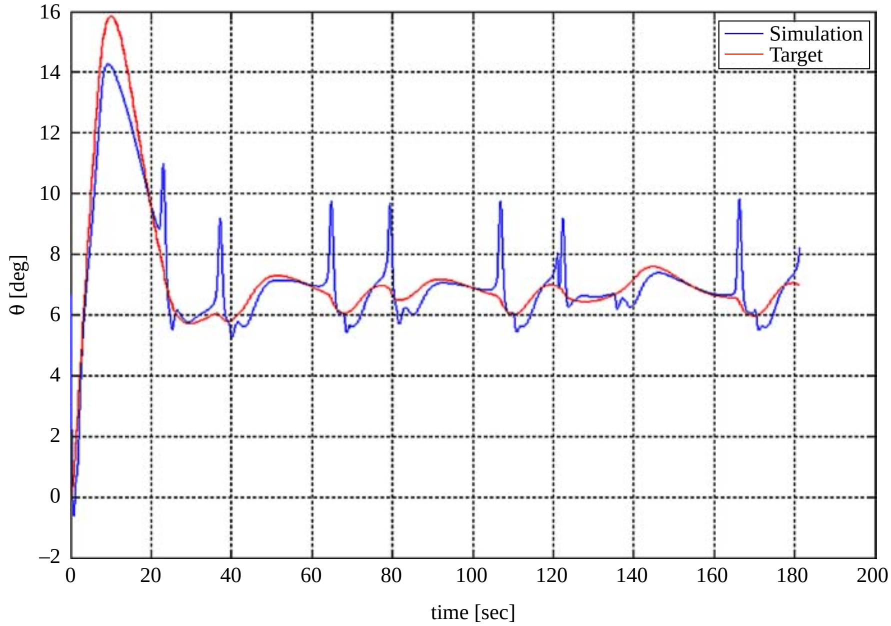
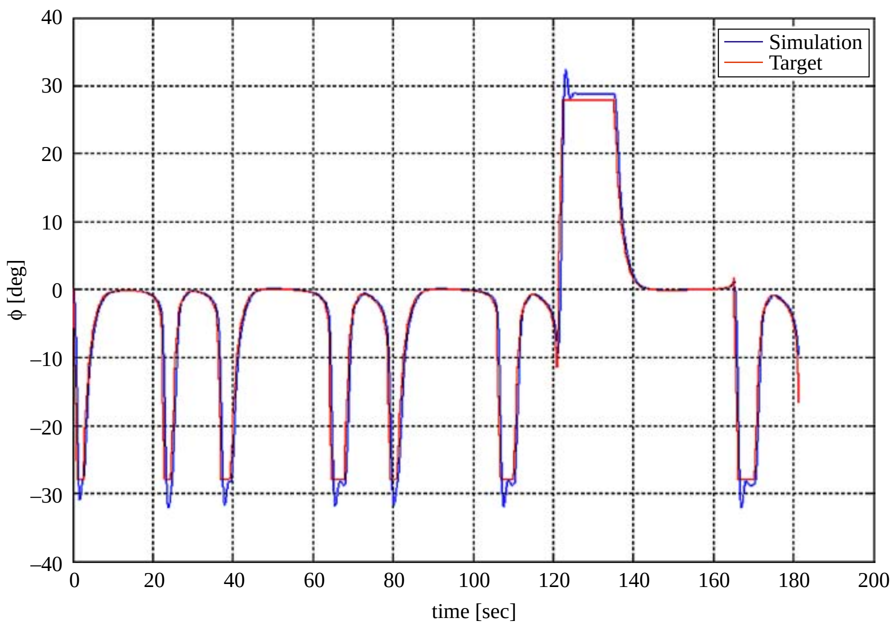


Figure 15 The roll response for the MH2000 platform



the same as that observed in simulation due to unavoidable modelling inaccuracies. Clearly, the better the mathematical model matches the real system, the lesser will be the effort required to conclude this experimental phase.

The same circuits performed in simulation are considered. Take-off and landing are manually by a remote pilot (pilot-in-command, indicated in red).

Flight tests showed that the results obtained in simulation are quite similar to the results of the real system. The little discrepancy is probably due to an anomalous behaviour of the autopilot during the first seconds in computer-in-command mode. In this period, the autopilot seems to suffer some trouble in navigation, and it commands abrupt manoeuvres, which obliges to use more conservative gains to keep the platforms flying under control. Of course, this represents a limitation on the achievable performance of the platform, a problem that becomes more evident for flight plans with short distances between waypoints (Figures 16-21).

9. Concluding remarks

The design of MAV is a tricky problem, considering the research activities involved in different disciplines, ranging

Figure 16 Four-waypoint square circuit real flight

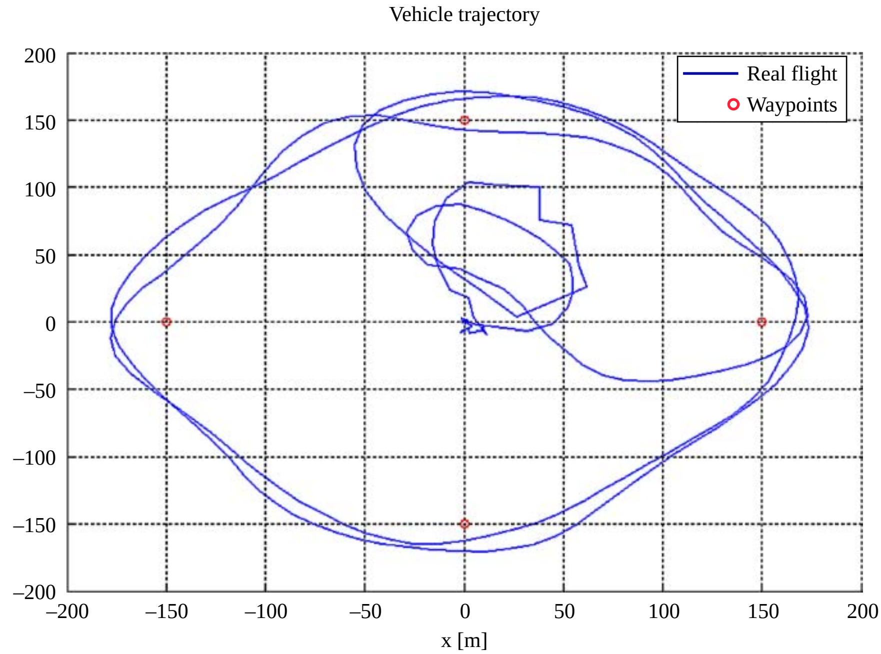
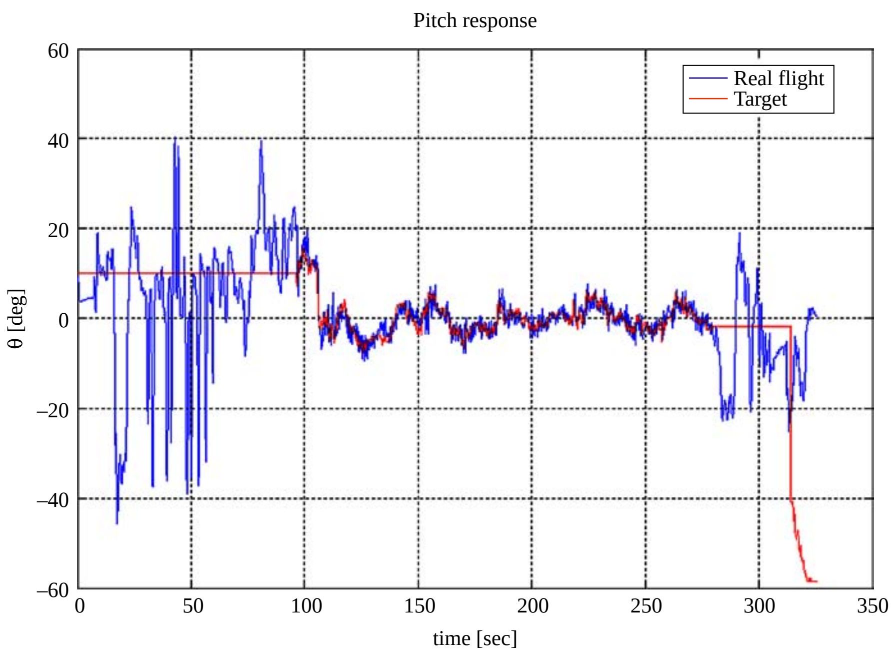


Figure 17 The pitch response for the MH600 real flight



from fluid dynamics to flight dynamics, from structure to on board systems, from FCS's to communications, in an extremely reduced scale. The MicroHawk program is a singular example of multidisciplinary research and development activity and engineers within a department of an Italian university.

The design of a flight simulator able to host the MicroHawk mathematical model permits to perform a real-time dynamic analysis, to verify flying and handling qualities for the different prototypes, and to define suitable mission profiles. This is a unique tool for evaluating the aircraft scale effects from the aeromechanics point of view.

Figure 18 The roll response for the MH600 real flight

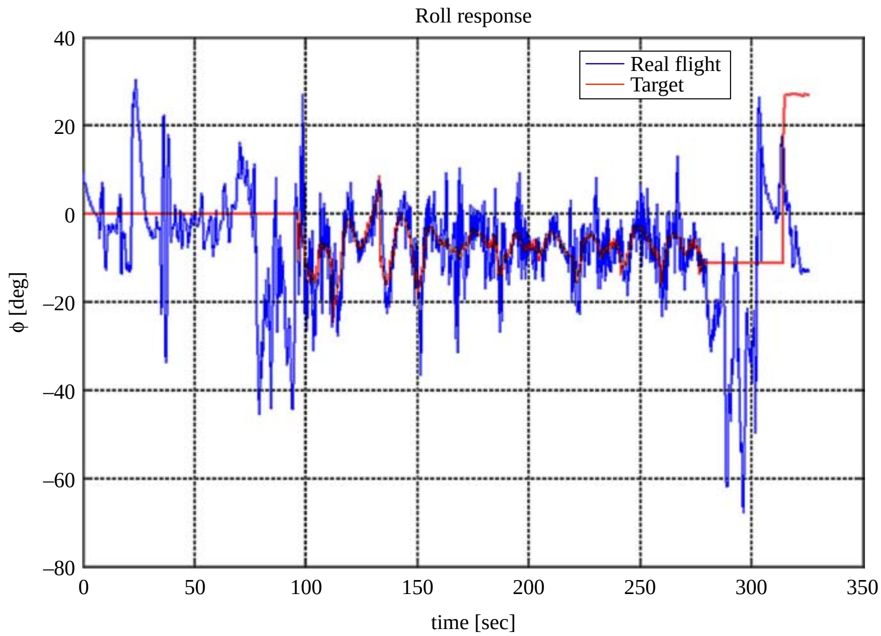
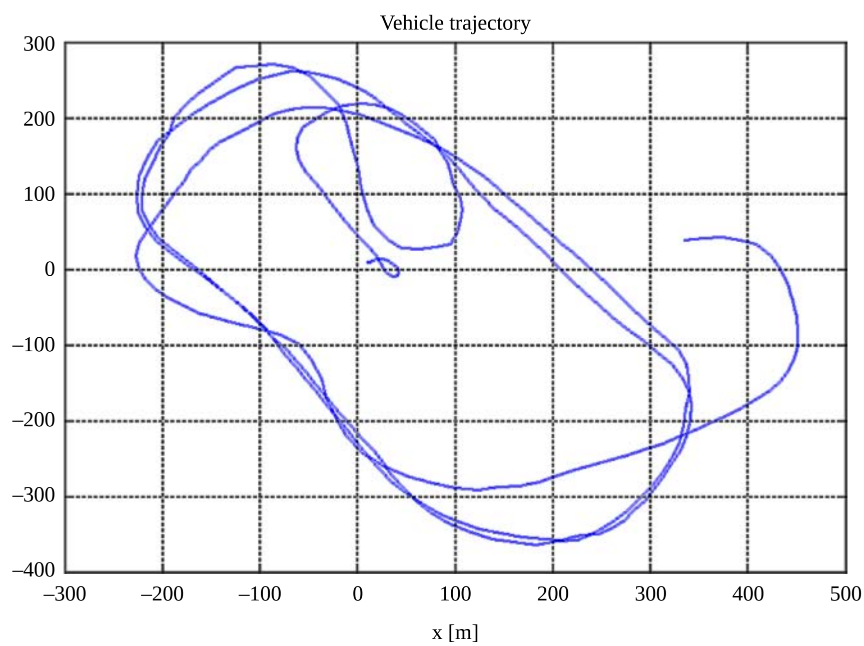


Figure 19 Four-waypoint rectangular circuit real flight



Flight tests confirm the qualities and the shortcomings for the prototypes studied and manufactured. Experiences with simulated mission profiles substantially reduced time-to-flight of the prototypes, but for autonomous flight operations the gain setting could be refined with real flights.

Taking into account the complexity of this kind of platform not only in the design phase, but also our experience has demonstrated the essential role of the simulation both in the design phase and in the operator training phase. In fact the support of the simulator permits to the end-user to be

Figure 20 The pitch response for the MH2000 real flight

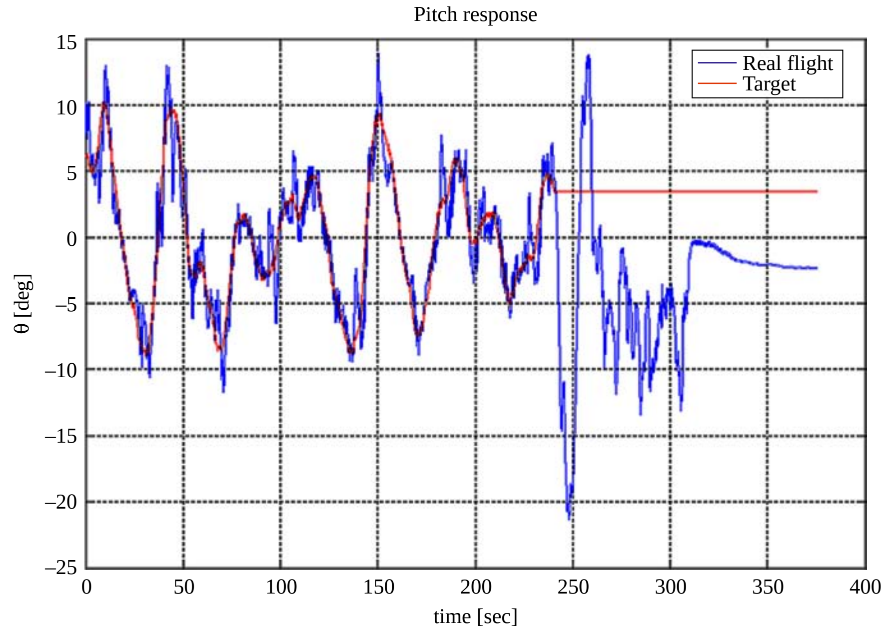
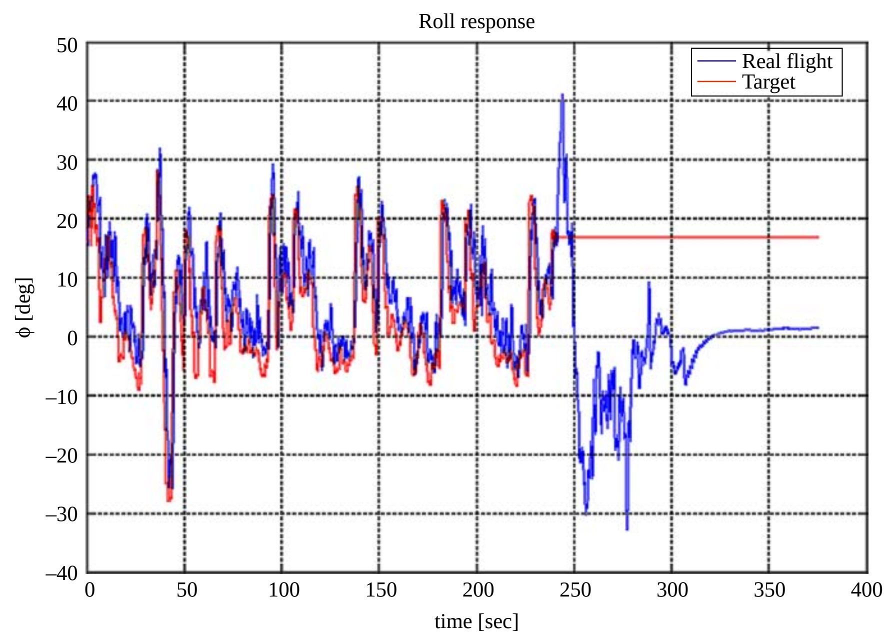


Figure 21 The roll response for the MH2000 real flight



confident with the MAV platform in remote piloting and in the autonomous flight.

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Further reading

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