Back to Session Subjects

AN “OFF THE SHELF” AVIONIC SYSTEM FOR ROTARY WING UAV RAPID PROTOTYPING

R. Pretolani[1], G. Saggiani[2], V. Rossi[3], B. Teodorani[4]

[1] II School of Engineering - University of Bologna
Via Fontanelle 40, 47100 Forlì, Italy
e-mail: pretolani@ingfo.unibo.it

[2] II School of Engineering - University of Bologna
Via Fontanelle 40, 47100 Forlì, Italy
e-mail: gianmarco.saggiani@unibo.it

[3] II School of Engineering - University of Bologna
Via Fontanelle 40, 47100 Forlì, Italy
e-mail: veronica.rossi@ingfo.unibo.it

[4] II School of Engineering - University of Bologna
Via Fontanelle 40, 47100 Forlì, Italy
e-mail: barbara.teodorani@ingfo.unibo.it

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Abstract: This paper presents the results, achieved at the Aerospace Engineering Department Laboratories of the University of Bologna - Italy (UNIBO), concerning the development of a “commercial off the shelf” (COTS) avionics system for rapid prototyping of small scale Rotary wing UAVs (RUAVs).

The RUAV avionics package was developed as an integrated modular system using commercial and cost effective technologies. The avionics package is comprised of sensors, computer and data link hardware as well as software to control the vehicle. The CompactRio (cRIO) system from National Instruments was chosen as flight computer due to its reliability and reconfigurable architecture, to enable fast and easy integration of different input/output hardware and sensors. The Hirobo 60 helicopter mechanics was used as flying platform and modified to accommodate the avionics hardware. A more powerful engine, longer fiberglass blades, longer tail boom and tail blades were also mounted in order to increase the helicopter payload carrying capabilities.

The avionic system was fast and easily programmable, resulting in a sudden speed-up of onboard hardware/software development and integration. The setup of this electronic package allowed recording of helicopter responses to pilot commands and provided deep insight into the small scale rotorcraft dynamics, facilitating the development helicopter models and control systems in the UNIBO Hardware In the Loop (HIL) simulator. A classical PI attitude controller was developed to test the avionics package control capabilities. First flight tests were performed in hovering conditions. Comparison between HIL simulation and experimental results showed good agreement.

1 INTRODUCTION

The increasing interest in military Unmanned Air Vehicles (UAVs) is fuelling an equally ambitious build-up in the civil community. It is well known that UAVs may represent a promising and cost-effective alternative to manned aircraft for a large number of civil applications [1]. Compared to traditional air vehicles, UAVs may offer significant advantages in terms of human safety (especially in dull, dirty and dangerous missions), operational cost reduction and work rate efficiency. Nevertheless, while research activities in UAV or Rotary Wing UAV systems are very advanced in the United States, UAV interest in Europe has begun only in the last years. As a result, the European Union has sponsored the UAV development program CAPECON, to attempt to kick-start a civil UAV industry in Europe and try to fill the gap with the United States. In the last years, UNIBO has carried out several research projects concerning the development and manufacturing of fixed wing UAV systems for the civil aviation market. For that reason, when the EU decided to start the CAPECON program, UNIBO didn't hesitate to take part in. Besides its partnership in the CAPECON program, UNIBO has also started a rotary wing UAV research program, since RUAV systems may represent an alternative to fixed wing UAVs (or even a more promising solution) for many UAV civilian applications due to their versatile flight modes, manoeuvrability and vertical take-off and landing capability. The main goal of UNIBO RUAV research program is to develop a helicopter capable of autonomous flight which could be used inside the Universities as a platform for researches in control and navigation laws; meanwhile it should be proposed as a technological prototype for industries interested in UAV development and manufacturing. One important aspect, derived from the above mentioned EU program, is the real need of applying proven technologies to the UAV world in order to take advantage of existing and cost effective technology [2,3]. For that reason, UNIBO has decided to evaluate the feasibility of using COTS sensors and electronics for its RUAV avionics package. This paper will first present the requirements that the avionic system should met in terms of desired system capabilities and physical constraints. The current UNIBO avionics package implementation will then be described. Finally, experimental flight tests performed for the avionic system validation will be compared with HIL simulations. Results will demonstrate the feasibility to use the designed avionic system for the UNIBO RUAV development, since it is able to provide accurate flight data measurements and high signal output rates which enable good helicopter control capabilities.

2 DESIGN REQUIREMENTS

The goal of UNIBO RUAV project is to develop a helicopter platform capable of autonomous flight which could be used inside the Universities for researches in control and navigation laws, man-machine interfaces and system integration; meanwhile it should be proposed as a technological prototype for industries interested in UAV development and manufacturing. In order to develop such kind of platform, avionic systems are required that enable the helicopter to maintain a stable attitude and follow desired trajectories. This avionics package is comprised of sensors, computer and data link hardware as well as software to guide, navigate and control the air vehicle. These aspects are particularly critical for helicopters, which are well known to be inherently unstable systems, and place numerous requirements on the avionic system design.

The main requirements taken into account for the avionics package design were both operational requirements and physical constraints. From this point of view the instrumented platform should:

- provide accurate flight data acquisition for dynamic model development and validation

- allow onboard implementation of feedback control laws and demonstrate good control capability
- be endowed with an onboard safety system in event of computer failure
- be versatile enough to enable fast and easy integration of different input/output hardware and sensors
- be as light as possible in order to lower the total platform weight and maintain good maneuver capabilities. Flight test demonstrated that the helicopter still has good maneuverability with 6 kg payload mass.
- be able to withstand the high vibration load typical of small scale helicopters. The primary sources of vibrations are the engine, the main rotor (spinning at roughly 22 Hz), the tail rotor and the tailboom bending resonance. These vibrations must be reduced to fit the operational vibration range of the onboard sensor and to provide accurate flight data measurements. Experimental tests performed with commercially manufactured elastomeric dampers showed that vibrations can be effectively reduced to the desired level.
- be protected against the electromagnetic and RF interference: common shielding precautions were used to isolate the onboard electronics from EM interference.

3 TEST VEHICLE AND AVIONICS DESCRIPTION

The test vehicle, shown in figure 1, is a Hirobo Eagle II 60 hobby helicopter which was modified to accommodate the avionics hardware. A more powerful engine, longer fiberglass blades, longer tail boom and tail blades were mounted in order to increase the helicopter payload carrying capabilities. The rotor diameter is 1.84 m and the platform total mass is about 11.2 kg. The assembly also includes a Bell-Hiller stabilizer bar, which augments servo torque with aerodynamic moment to change the blades cyclic pitch and adds lagged rate feedback to improve the helicopter handling qualities.

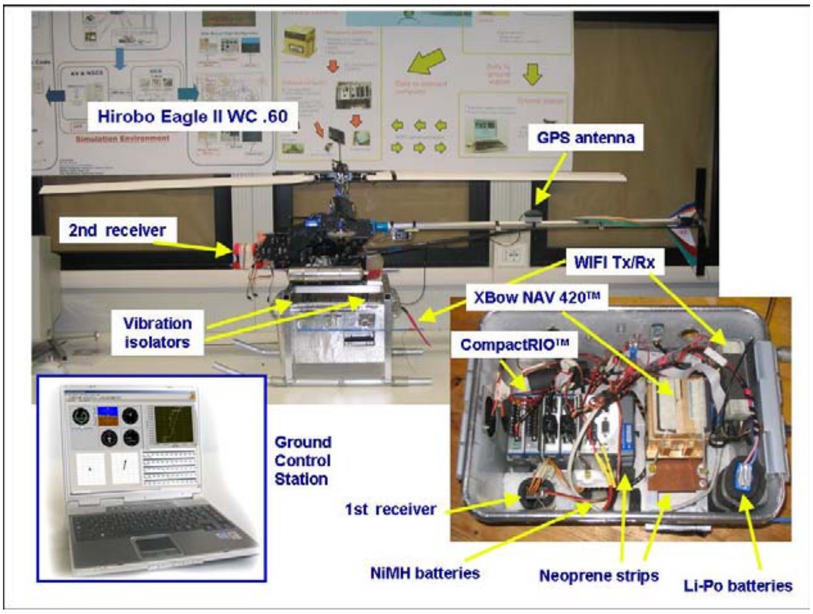
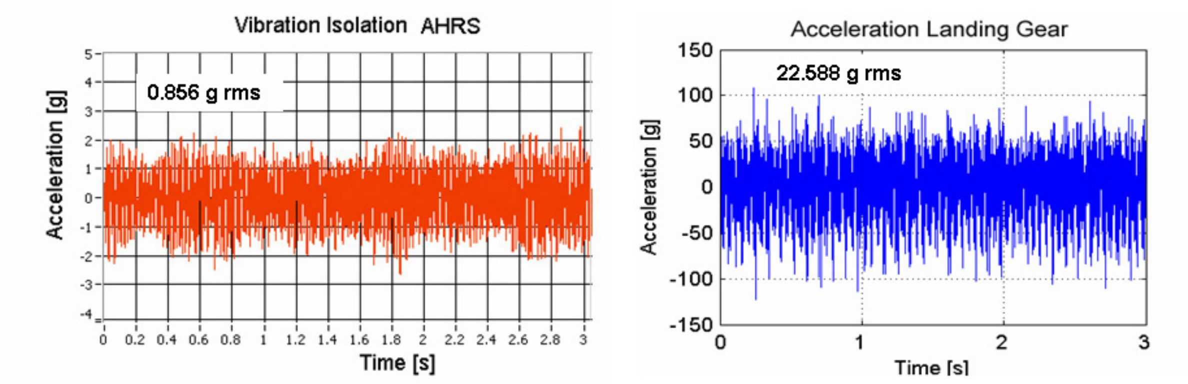


Figure 1: RUAV hardware

3.1 Avionics hardware and onboard software

The design constraints, described in section 2, were met with a 4.5 kg aluminum shielded avionics box (see fig. 1) mounted on a customized landing gear and suspended with elastomeric isolators. The suspension system effectively attenuates vibration inputs from the main rotor and the engine to a level well within the operational vibration range of the avionics package (see fig. 2).



CRIO Operating Vibration Range : < 5 g rms 10Hz-500Hz

NAV 420 Operating Vibration Range: < 6 g rms 20Hz-2kHz

Figure 2: RUAV operating vibration range

The complete avionics architecture is shown in figure 3.

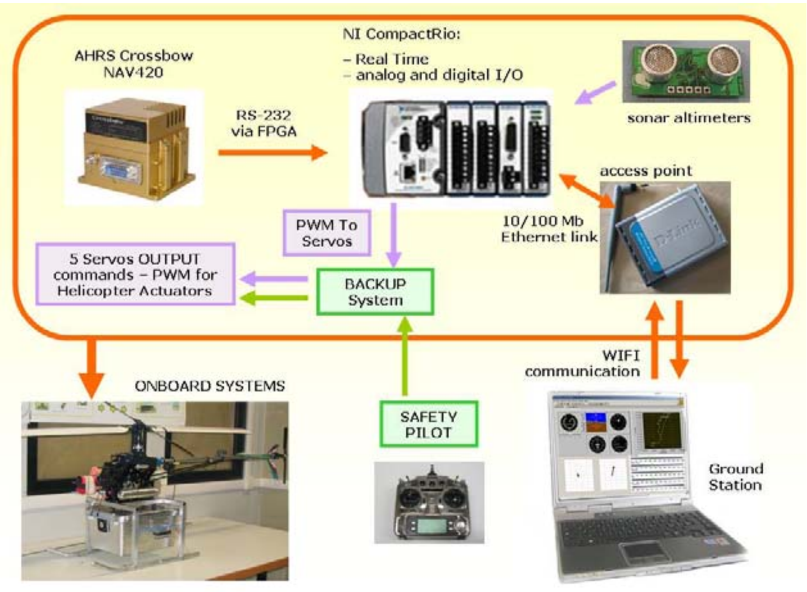


Figure 3: RUAV system architecture

The NI CompactRIO system was chosen as flight computer in order to manage flight data acquisition and helicopter control. It is a complete reconfigurable embedded system which consists of a real-time processor and a reconfigurable chassis containing user-programmable FPGA modules and other swappable industrial I/O modules. The CRIO real time core is an industrial 200 MHz Pentium processor which contains 64 MB of DRAM memory and 512 MB of nonvolatile CompactFlash memory for flight data storage. It includes also 1 serial port and a 10/100 Mb network port for connection to a wireless access point. The I/O modules contain built-in signal conditioning, isolation and I/O connectors for direct connections to sensors and actuators. The sensor package, installed on the UNIBO RUAV, includes a Crossbow NAV420 GPS-aided Attitude Heading Reference System (AHRS) and ultrasonic sensors which provide accurate altitude measurement with a resolution of 2 cm. Two separated radio receivers (one inside the avionics box and one mounted on the helicopter frame) and electronic switches are also installed in order to give back helicopter control to the R/C pilot in event of computer failure.

The onboard software has been developed in Labview code and then compiled into the CRIO FPGA and real time modules. Particularly, the FPGA code:

- reads PWM commands from the radio receiver inside the avionics box
- acquires helicopter attitudes, angular rates, velocities and position, provided by the Crossbow NAV 420 with 100 Hz updates, using an RS232 protocol. The RS232 protocol has been managed using the FPGA Digital Input to guarantee deterministic data acquisition.
- acquires altitude measurement from the ultrasonic sensor using an I2C protocol
- manages a PID based control loop for helicopter control closed at 50 Hz. At present the PID loop controls main rotor cyclics while collective pitch is left to the pilot and tail rotor collective to the onboard gyroscope. In manual mode, the FPGA code sends the original pilot commands directly to the servos; in automatic mode, the controller generates commands based on the reference attitude to be maintained. The two flight modes are chosen via radio switch. A second radio switch is used to disable the onboard computer in event of electronics failure: in this safety mode, commands are sent to the servo by means of the second radio receiver mounted on the helicopter airframe.

The CompactRIO real time processor receives sensor information from the FPGA and records all the flight data; meanwhile it manages also wireless Ethernet communication with the ground control station. The ground control station software is also developed in Labview and runs on a laptop computer. The remote graphical user interface is constituted by two windows (the virtual cockpit window and the telemetry window) for real time display of flight data information (fig. 3). Additional information is available such as GPS and inertial measurement unit status and system warnings. The ground operator can initiate and terminate the flight software or interact with the program starting and stopping the onboard data logging.

4 AVIONICS PACKAGE VALIDATION

The validation procedure followed for the avionic system is shown in figure 4.

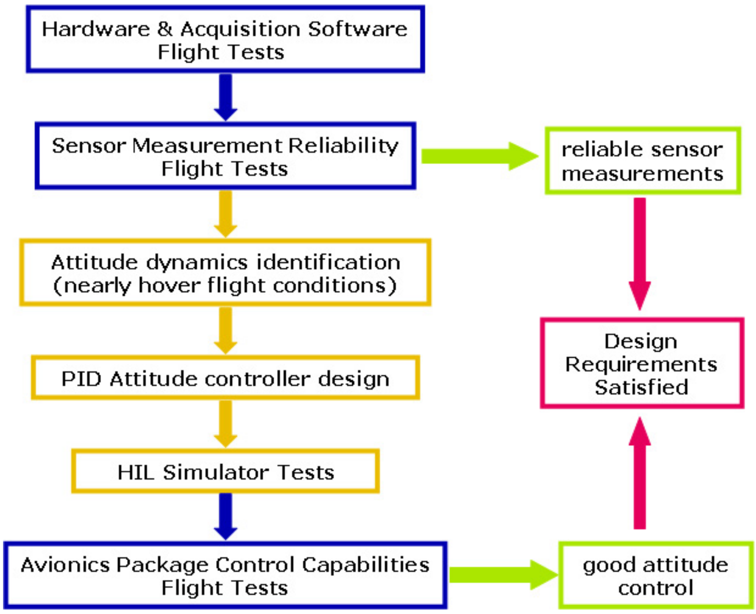


Figure 4: Avionics package validation process

First a series of flight tests was performed in order to validate the avionics hardware and flight data acquisition software. The collected data were then analyzed for evaluating the dynamic characteristics of the small scale helicopter and roll/pitch rate transfer functions were identified in nearly hover flight conditions. Afterwards, a classical PI attitude controller was modelled for pitch and roll angles, neglecting cross-coupling between the helicopter inputs, and was tested in a HIL simulator. Experimental results showed that the avionic system is able to satisfy design requirements providing reliable sensor measurements and good attitude control capabilities. The results of the validation procedure are detailed in the next sections.

4.1 Onboard sensor measurements

The UNIBO RUAV avionics hardware was successfully tested in flight. Flight data were transferred from the air vehicle back to the Ground Control Station (GCS) via wireless data links.

All onboard electronics worked properly while sensor data was recorded at 100 Hz. AHRS raw data (figure 5) show vibration disturbances.

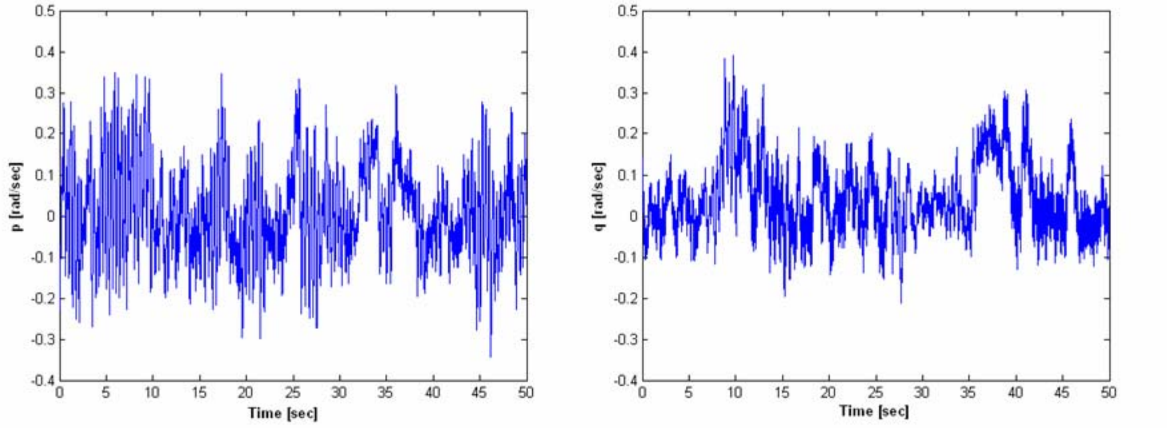


Figure 5: Example of pitch and roll rate AHRS raw data

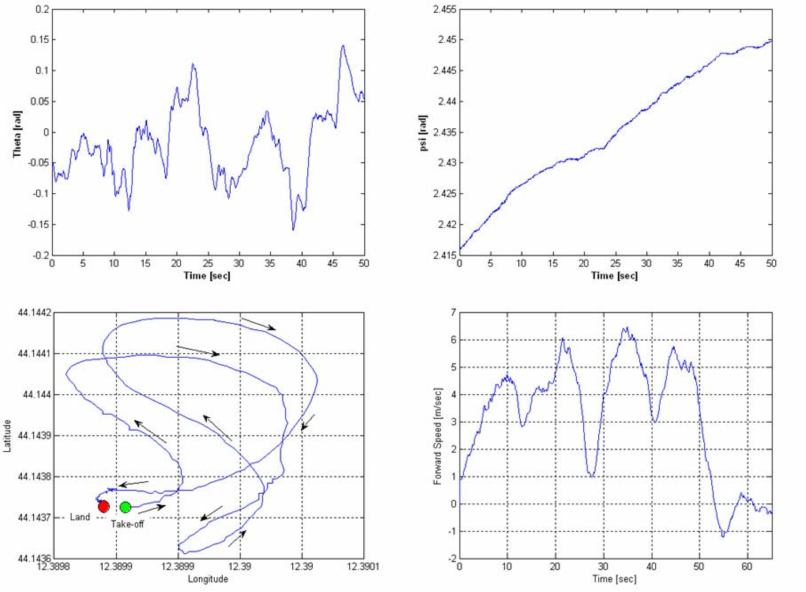


Figure 6: AHRS filtered flight data

However, thanks to the XBow NAV420 integrated Kalman filter, smooth and stable GPS position information, velocity and attitude measurements were available, which can be used for control and navigation system implementation. Figure 6 shows examples of sensor data measurements taken while the helicopter was overflying the test field at low speed conditions. Ultrasonic sensors were also tested. First they were calibrated at ground and then mounted on the avionics box, using neoprene strips for vibration isolation. Recorded flight tests showed good experimental results although they can provide reliable altitude measurements only up to 5.5 m (see fig.7).

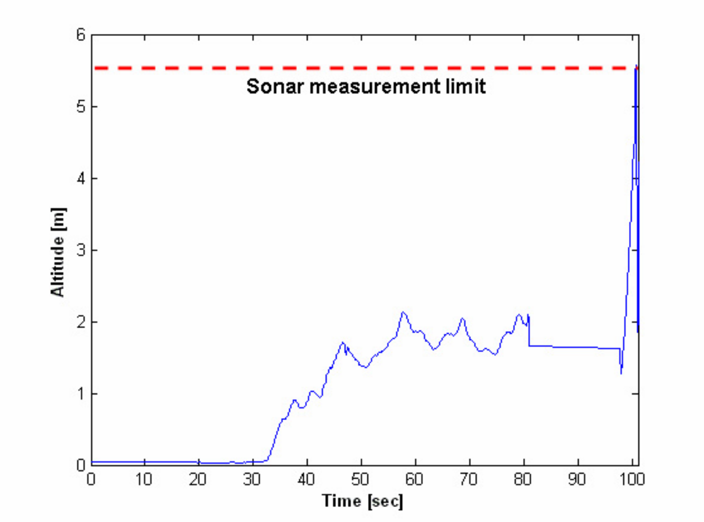


Figure 7: Sonar sensors measurements

4.2 Attitude rate transfer function model

In his work, Mettler [4,5] showed that small scale helicopters exhibit all similar characteristics which, for the attitude rate dynamics, are very close to those of a second order system. The pitching and roll rates dynamics, for low-speed flight only, can be approximated through the following transfer functions:

$$\frac{q}{\delta_{long}} = \frac{A_{long}}{\tau_e} \frac{\omega_{nq}^2}{s^2 + 1/\tau_e s + \omega_{nq}^2} \qquad (1)$$

$$\frac{p}{\delta_{lat}} = \frac{B_{lat}}{\tau_e} \frac{\omega_{np}^2}{s^2 + 1/\tau_e s + \omega_{np}^2} \qquad (2)$$

In the equations:

- ω_{nq} and ω_{np} are the natural frequencies of the longitudinal and lateral fuselage-rotor-bar modes
- τ_e is the effective rotor time constant for the flapping motion taking into account the effect of the stabilizer bar. A_{long} and B_{lat} are the effective cyclic control derivatives taking into account the effect of the stabilizer bar.

These assumptions were confirmed from experimental flight data records.

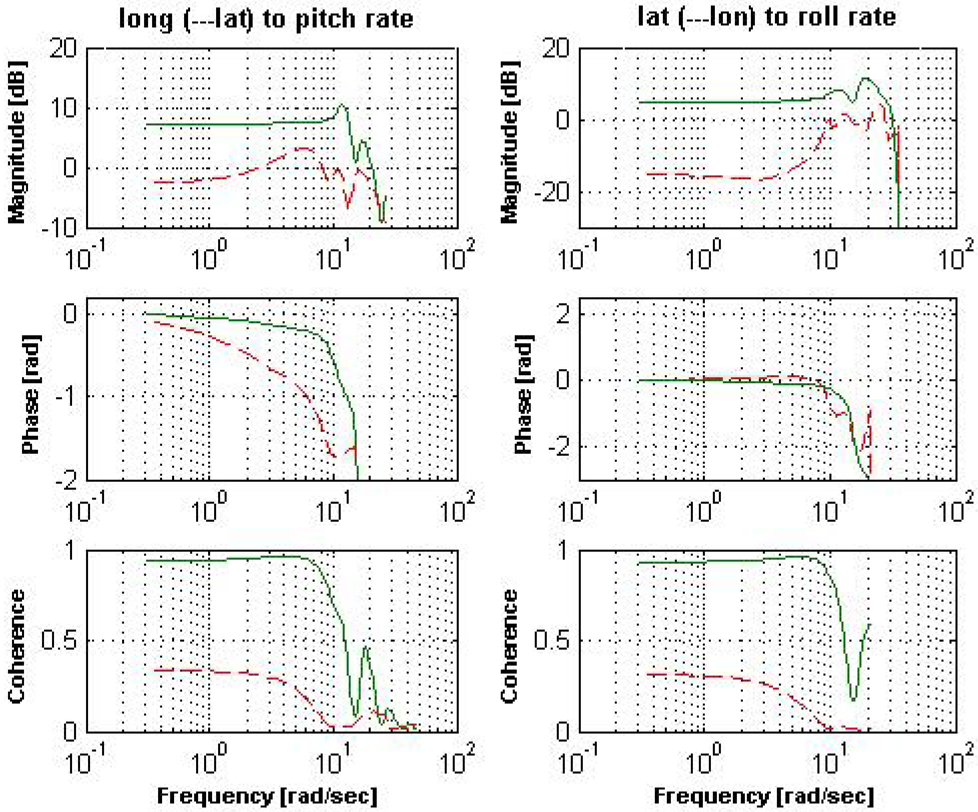


Figure 8: Pitch and roll rate estimated frequency responses to longitudinal and lateral cyclics

Figure 8 shows the estimated experimental frequency response for the on- and off-axes roll and pitch angular rates to frequency sweep longitudinal and lateral cyclic inputs, as well as the values of the respective coherence functions. Both on-axes pitch and roll rate responses q/δ_{long} and p/δ_{lat} exhibit well defined characteristics of a second-order system. The transfer function parameters in equation 1 and 2 were identified using the Simulink™ Signal optimization toolbox. The parameter initial values, to be used in the optimization algorithm, were estimated from the vehicle mass-geometry characteristics reported in table 1 .

Particularly:

- referring to table 1, ω_{nq} and ω_{np} are given by

$$\omega_{nq} = \sqrt{\frac{T_{mr} h_{mr} + k_{\beta}}{I_{yy}}} \qquad (3) \qquad\qquad \omega_{np} = \sqrt{\frac{T_{mr} h_{mr} + k_{\beta}}{I_{xx}}} \qquad (4)$$

  For nearly hover conditions $T_{mr} \cong mg$. The distance between the main rotor hub and the helicopter center of gravity h_{mr} was measured. The moments of inertia I_{xx} and I_{yy} were determined with the torsional pendulum test. The hub torsional stiffness k_{β} was evaluated from static measurements. The values, estimated for the natural frequencies ω_{nq} and ω_{np}, were also confirmed from flight tests: in figure 8, the frequency response magnitude peaks at around 12 rad/sec for the pitch rate and 18 rad/sec for the roll rate
- an approximated value of τ_e is given by $\tau_e = 16/(\gamma_{fb}\Omega_{mr})$ [5], where γ_{fb} is the Lock number of the stabilizer bar and Ω_{mr} is the main rotor speed. Therefore a starting value for τ_e was estimated from geometry and vehicle physical characteristics (see table 1)
- a reasonable initial value for A_{long} and B_{lat} was estimated from ref [5].

Parameter	Description	Source
$m = 11.2\ \text{kg}$	Helicopter mass	Measured
$I_{xx} = 0.30\ \text{kg}\cdot\text{m}^2$	Rolling moment of inertia	Torsional Pendulum Test
$I_{yy} = 0.79\ \text{kg}\cdot\text{m}^2$	Pitching moment of inertia	Torsional Pendulum Test
$I_{zz} = 0.57\ \text{kg}\cdot\text{m}^2$	Yawing moment of inertia	Torsional Pendulum Test
$K_\beta = 80\ \text{N·m/rad}$	Hub torsional stiffness	Static Measurement
$\gamma_{fb} = 0.8$	Stabilizer bar Lock number	Calculated
$c_{fb\ ext} = 0.35\ \text{m}$	Stabilizer bar external radius	Measured
$c_{fb\ int} = 0.235\ \text{m}$	Stabilizer bar internal radius	Measured
$c_{fb} = 0.06\ \text{m}$	Stabilizer bar chord	Measured
$a_{fb} = 2.67\ \text{rad}^{-1}$	Stabilizer bar lift curve slope	Estimated ref. [5]
$I_{\beta fb} = 0.003\ \text{kg}\cdot\text{m}^2$	Stabilizer bar flapping inertia	Estimated ref. [4]
$\Omega_{nom} = 138\ \text{rad/s}$	Nominal main rotor speed	Measured
$R_{mr} = 0.92\ \text{m}$	Main rotor radius	Measured
$c_{mr} = 0.07\ \text{m}$	Main rotor chord	Measured
$a_{mr} = 5.3\ \text{rad}^{-1}$	Main rotor blade lift curve slope	Estimated ref. [5]
$I_{\beta mr} = 0.071\ \text{kg}\cdot\text{m}^2$	Main rotor blade flapping inertia	Torsional Pendulum Test

Table 1: UNIBO RUAV parameters

The identified parameter values are reported in table 2.

Identified Parameters				
$\boldsymbol{A_{long}}$ [rad/rad]	ω_q [rad/sec]	$\boldsymbol{B_{lat}}$ [rad/rad]	ω_q [rad/sec]	τ_e [sec]
0.30025	12.1	0.22078	18.1	0.132

Table 2: Identified transfer functions parameters

The pitch and roll rate response q/δ_{long} and p/δ_{lat} were then used to identify two third order transfer functions for the roll and pitch angle, which were used for the PID attitude controller as described in the next section. Figure 9 shows good time domain response agreement between experimental data and the model-predicted responses to pilot input. Note that time domain comparison was made using control inputs and experimental data different from the one used in the identification process.

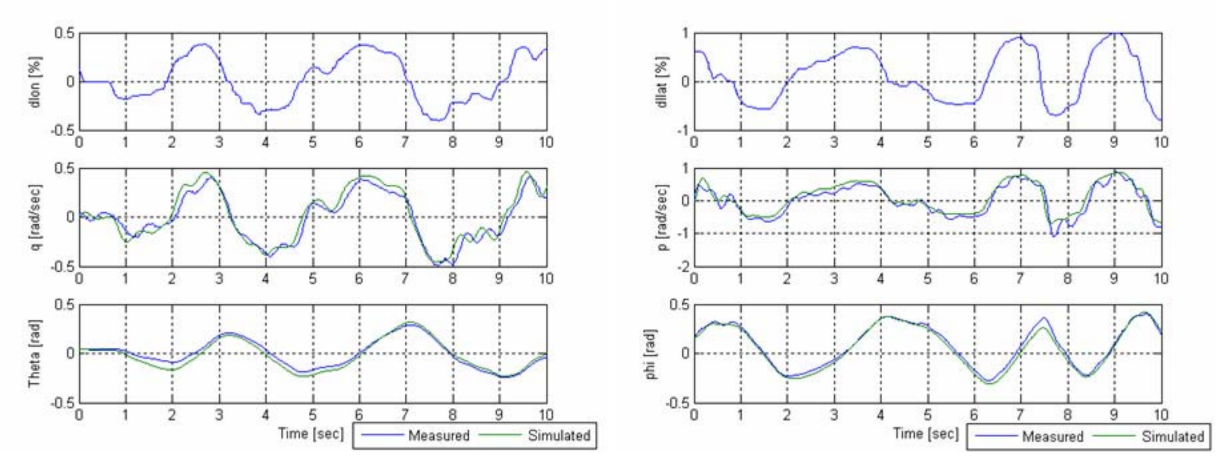


Figure 9: Comparison between simulated and experimental helicopter responses

The Matlab *BEST FIT* parameter was used as index to evaluate the agreement between simulation and experimental results. By definition, it is given by the following equation:

$$BEST\ \ FIT = \left[\frac{1 - norm(y_{meas} - y_{sim})}{norm(y_{meas} - mean(y_{meas}))} \right] \tag{5}$$

The computed values were 80% for the pitch angle and 76 % for the roll angle (usually a *BEST FIT* index greater than 70% is considered a good agreement level).

4.3 Classical PI control design in the HIL Simulator

In order to test the feasibility to use the installed avionic hardware and software for helicopter control, a simple PI pitch and roll attitude controller was implemented [6,7]. Yaw attitude control was performed by the onboard gyroscope, while altitude control was still left to the R/C pilot. The optimization toolbox of Matlab was used to obtain the PI controller's gains. For the PI controller design, cross-coupling between the helicopter inputs was neglected. The coherence function diagrams together with the small magnitude of the off-axes responses (see figure 8), provide good experimental feedback for this assumption. By definition, the coherence function is a correlation metric between two input-output signals which attains a maximum value of unity when the two signals are fully correlated at a frequency point. Figure 8 shows that for on-axes responses the coherence function reaches unity almost up to 8-10 rad/sec and then falls sharply due to the limited pilot bandwidth. Conversely, in the off-axes responses it is about 0.3-0.4, thus demonstrating the low correlation level between the pitch rate and the lateral cyclic input as well as between the roll rate and longitudinal cyclic. The PI gains values are reported in table 3.

	K_P	K_I
PITCH	0.7737	0.0822
ROLL	1.0418	0.1134

Table 3: PI controller gains

To allow safe, risk-free testing, the PI controller was first implemented in a HIL simulator [8,9] which is shown in figure 10.

The HIL simulator is constituted by:

- an exact duplicate of the flight computer (the CRIO System) and of the onboard software including the attitude PI controller. Reference value to the controller are given by means of the R/C transmitter and then acquired by the CRIO software from the R/C receiver.
- a computer which simulates the helicopter pitch and roll dynamics through the identified transfer functions and the onboard sensor outputs (in this simplified model, states outputs are θ, q, u, φ, p, v). The simulation computer contains also an identified actuators transfer function which receives inputs from the PI controllers by means of a signal acquisition card and send commands to the dynamics simulator
- an OpenGL visual system for rendering the helicopter as it moves around in a virtual scenery

Figure 11 shows the good agreement between HIL simulation tests and the experimental flight results for the roll angle, thus demonstrating the effectiveness of the designed UNIBO avionic system for RUAV control.

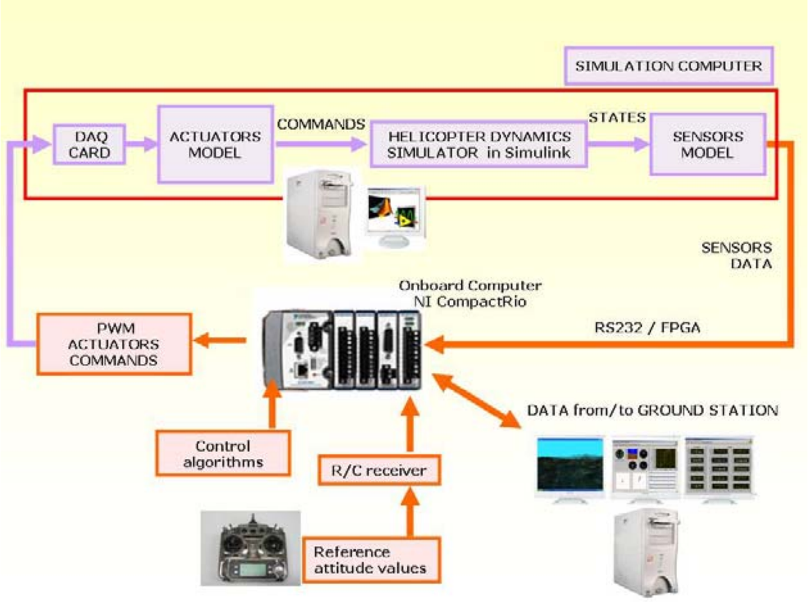


Figure 10: UNIBO HIL simulator

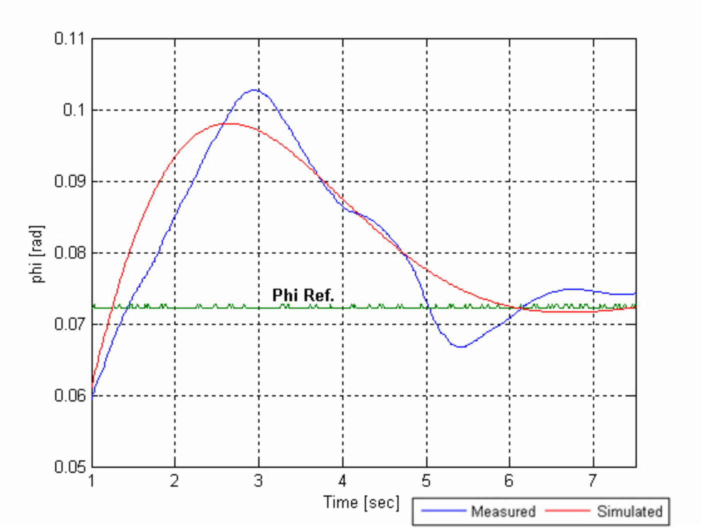


Figure 11: Roll angle simulated and experimental response to PI controller

CONCLUSION AND OUTLOOK

An avionics package was set up for the UNIBO RUAV using commercial and cost effective technology. HIL simulations and experimental flights were performed in order to test the feasibility to use the avionics hardware and software for helicopter identification model and control system development. A simple PID controller was designed based on two identified transfer functions for the helicopter roll and pitch angle. Results demonstrated that the avionics system is able to provide accurate flight data measurements for dynamic model identification and helicopter control capabilities. In the near future, the project will continue with the development of a full-envelope helicopter model. A velocity and position controller will be also added to the existing attitude PID controller and further experimental flights will be performed. The developed RUAV platform will then be used inside the University as flying test bed for researches in control and navigation laws, man-machine interfaces and system integration. The feasibility to install the designed avionics package, integrated with additional redundant systems, on an ultralight helicopter will be also investigated.

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