

The role of laboratory activities in aerospace control education: two case studies

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Abstract: Aerospace control education can significantly benefit from actual hands-on experience. In most cases, however, such experience can only be provided to students in small-scale project activities. In this paper the experience gathered in integrating laboratory activities in aerospace control education in the UAV Lab and in the Advanced Aerospace Control courses is presented and discussed. UAV Lab is an extra-curricular course aimed at an interdisciplinary group of students covering the whole design cycle for a multirotor UAV, from conceptual design to in-flight validation, with specific emphasis on hands-on experience in hardware/software integration, data collection and analysis and flight testing. Advanced Aerospace Control, on the other hand, is a curricular Master course in robust and nonlinear control, in the framework of which students are requested to solve a control design problem formulated over the dynamics of a multirotor UAV. The paper presents the course syllabi, discusses the role of laboratory activities and provides an overview of the obtained results.

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1. INTRODUCTION

In recent years Unmanned Aerial Vehicles (UAVs), which in the past had been of interest only for military applications, have started to play a significant role in civil applications as well, ranging from personal and commercial use to countless industrial applications. In the framework of civil applications, multirotor UAVs represent the most common architecture, due to their versatility and reliability. As a consequence, education activities related to the design of multirotor UAVs and the related problems in guidance, navigation and control have become more and more widespread, with courses covering both specific disciplinary aspects of their design and operation (aeromechanics, power electronics, hardware and software, navigation, control, telemetry/communications *etc.*) and system-level design issues (see, *e.g.*, Gaponov and Razinkova (2012) Khan et al. (2017)).

In this paper the experience gathered in integrating laboratory activities in aerospace control education in the UAV Lab and in the Advanced Aerospace Control courses is presented and discussed. The UAV Lab course aims at providing teams of students the opportunity to carry out design activities in the field of multirotor UAVs. More precisely, the course, aimed at an interdisciplinary group of students comprising Master students in Aeronautical Engineering, Space Engineering, Automation and Control Engineering and Computer Engineering, covers the whole design cycle for a multirotor UAV, from conceptual design to in-flight validation, with specific reference to modelling, simulation, identification and control. As will be discussed in the following section, the course has been conceived as an extra-curricular activity, taking place outside regular

class hours and during weekends, so the emphasis is not on conventional lectures but rather on hands-on experience in hardware/software integration, data collection and analysis and flight testing. Advanced Aerospace Control, on the other hand, is a curricular Master course in robust and nonlinear control, in the framework of which students are requested to solve a control design problem formulated over the dynamics of a multirotor UAV, with the opportunity of testing their solution in flight.

The paper is organized as follows. The UAV Lab course is presented in Section 2, with specific reference to the approach, the syllabus and a description of the sizing approach used by the student teams to carry out the conceptual design activities and the requirement specifications provided to the student teams. The Advanced Aerospace Control course is then presented in Section 3, in terms of the syllabus and of the description of the control design projects which the students are required to address as part of the course. Finally Section 4 provides a discussion of the overall course experience, some lessons learned and a few perspectives for further developments.

2. UAV LAB

The UAV Lab course was organised and managed according to the following approach:

- a call for the definition of interdisciplinary student teams was sent to Master students in Industrial and Information Engineering of Politecnico di Milano in view of the direct relevance to the course topic in technical terms.
- Introductory lectures were prepared to provide all participating students with a common background

on multirotor UAVs, to ensure that each of the teams would be able to work together on UAV design problems. Exercises in multirotor UAV sizing were also carried out to make sure the students actually grasped the overall design methodology.

- Subsequently, design specifications to be implemented by the students were presented in detail and students were allocated to corresponding interdisciplinary design teams.
- Each team then carried out a preliminary design for a multirotor, using the methods and tools presented in the introductory lectures. Such designs were then reviewed by the instructors.
- Detailed designs were subsequently carried out by the student teams and the outputs of the detailed designs, (CAD drawings of the multirotors and corresponding bills of materials), were then reviewed.
- Having reached an appropriate maturity for the designs, the components (flight control and companion computers, blades, motors, electronic speed controllers, batteries, materials for mechanical integration) needed for platform integration were acquired (or, in some cases such as carbon-fiber frames, manufactured to design).
- As in the design of multirotor UAVs most of the modelling uncertainty is associated with the propulsion subsystem (Electronic Speed Controllers (ESCs), motors and propellers), dedicated data-collection experiments were carried out to characterise such subsystems (see Giurato et al. (2019) for details).
- Customisation of simulation model: the numerical values of the parameters obtained from the experimental characterisation were used to fine-tune the general-purpose MATLAB/Simulink model for multirotor UAVs to suit each of the designed platforms.
- Integration: the student teams then took care (with some support from the instructors) of the mechanical, electrical and electronic integration of the platforms.
- Flight-testing: flight-testing was used to fine-tune the controller parameters starting from the ones determined in simulation. As a last step, endurance tests were carried out to compare actual to required performance.

The course activities have taken place in the Flying Arena for Rotorcraft Technologies of Politecnico di Milano (Fly-ART, see Figure 1), a facility which has been designed to support not only research activities in the field of multirotor UAVs but also education ones, with specific reference to guidance, navigation and control systems. More precisely, Fly-ART includes an indoor flight-test facility with a $290m^3$ flight space covered by a 3D motion capture system, a few work stations for hardware integration and a classroom which can seat up to 25 students.

The above-mentioned introductory lectures were aimed at providing all the students an appropriate common ground on multirotor UAVs, including principles of operation, architecture and main characteristics from the point of view of preliminary design. In detail, the lectures covered the following topics:

- Course introduction and overview of multirotor UAVs: the first lectures were aimed at providing some basic information about the organisation of the course and,



Fig. 1. The FlyART facility at Politecnico di Milano.

an overview of multirotor UAVs, in terms of basic principles of operation, modelling (rigid body, motors, propellers, sensors), simulation, model identification and attitude and position control. Note that all the involved students have a sound background in dynamic systems, linear control theory and parameter estimation, so that the above topics could be covered in a very efficient way.

- Subsystem decomposition and modelling for sizing: two lectures were devoted to the illustration of the main subsystems into which a typical multirotor UAV can be decomposed, namely frame, propulsive system, power supply, electronics and payload. For each subsystem the key parameters playing a role in the sizing were highlighted.
- Formulation of sizing problems and development of a simple sizing tool: a simple approach to the sizing of a multirotor UAV was then presented and the students were asked to both implement their own version of the sizing algorithm and test it using predefined numerical examples.
- Introduction to eCalc: for validation purposes, the online multirotor sizing tool eCalc (see Solution for All Markus Mueller (2019)) was also presented and used to double-check the results of the numerical examples.

Topic	Lectures (h)
Course introduction	1
Overview of multirotor UAVs	1
Subsystem decomposition	1
Modelling for sizing	1
Formulation of sizing problem	1
Development of sizing tool	1
Introduction to ecalc	1
Presentation of design specifications	1

Table 1. Syllabus for lectures.

The design approach used in the framework of the UAV Lab course is based on the assumptions outlined in the following. The flight time is computed considering a hovering static flight condition. Clearly, in a real flight scenario the flight time will be smaller, according to flight speed, environmental conditions *etc.* Aerodynamic considerations are neglected at this preliminary level. Furthermore note that, if needed, a size constraint requirement could be considered during the components selection phase. Also, since a specific thrust value can be produced by many motor/propeller pairs, the right choice is considered as the one closer to the required use: in general, a bigger rotor is also more efficient. The procedure can be summarised as follows (see also Figure 2):

- define requirements for Maximum Take-Off Weight (MTOW) and endurance (*i.e.*, flight time).
- Translate the requirements into physical quantities, *i.e.*, maximum thrust and energy.
- Select the components of the UAV so as to satisfy the given thrust and energy requirements (forward design).
- Verify by analysis that the solution is feasible and close to the initial requirements (inverse design) and iterate if necessary.

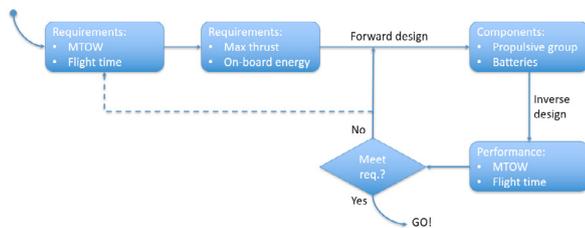


Fig. 2. Block diagram of the design approach.

The students were divided in teams making sure that each group had the required multidisciplinary character aimed for from the outset of the initiative. Three sets of design requirements were then provided to the students. In particular, the specified designs were defined based on recent and ongoing research activities within the Aerospace Systems and Control Laboratory (ASCL) of Politecnico di Milano, specifically on the problem of air-to-air landing of multirotor UAVs (see Giuri et al. (2019)) and on the design, prototyping and control of thrust-vectoring multirotor UAVs (see Invernizzi and Lovera (2018)). It is important to point out that unlike similar courses in which students are constrained to use components taken from predefined kits, within UAV Lab the preliminary and detailed design activities are completely free, so a suitable bill of materials has to be produced by each team. Only a single constraint was placed, namely the use of a flight control computer based on the PixHawk standard (see Pixhawk Special Interest Group (2020)) and of the PX4 autopilot (see PX4 (2020)), for compatibility with the laboratory standard platform and with the ANT-X customisation system for the control modules (see ANT-X (2020)).

Air-to-air refuelling is a well-known problem which may arise when undertaking long-range flights. In the military field, Air-to-Air Automatic Refuelling (AAAR) involving fixed-wing drones is object of studies and research activities. Also small UAVs suffer from low endurance problems, since most of them have an electric propulsion system. A possibility to extend the range of UAV missions could be to have a carrier drone, possibly a fixed-wing one, with several lightweight multirotors aboard, which can take-off from and land on it. The study of automatic air-to-air landing requires the availability of two custom-designed platforms:

- a *carrier* drone designed to be as insensitive as possible to the perturbations caused by landing and to offer a wide, flat, "landing-pad-like" surface to carry out landing experiments in a simple and safe way;
- a lightweight and agile drone, to be used as a *lander*. For the lander a requirement specification inspired by

high-agility First-Person View (FPV) racing drones has been proposed to the students.

In view of this, the design requirements were formulated.

As for thrust-vectoring multirotor UAVs: in recent years the development of multirotor UAVs with thrust vectoring capabilities has received a growing interest. These systems can achieve a larger degree of actuation compared to coplanar multirotor UAVs since both thrust and torque can be oriented within the airframe. This feature makes thrust-vectoring UAVs capable of performing complex full-pose maneuvers, which is particularly attractive for inspection-like applications that may require, for instance, navigation in a constrained environment. Moreover, being able to deliver both force and torque in any direction enhances the UAV interaction capabilities with the environment, which is especially desirable in aerial manipulation tasks. Two main technological solutions have been proposed to endow multirotor UAVs with thrust vectoring capabilities: by employing tilttable propellers Ryll et al. (2015); Kastelan et al. (2015); Invernizzi et al. (2018) and by mounting the propellers in a fixed, non-coplanar fashion Crowther et al. (2011); Rajappa et al. (2015); Brescianini and D'Andrea (2016). In the UAV Lab course one of the student teams was asked to propose a design for a thrust-vectoring multirotor UAV belonging to the first class. The main points of the corresponding design specification therefore require that the UAV includes independent tilting mechanisms for each of the arms, to be treated as a payload in the mass budget of the UAV.

Starting from the lectures and the design approach and requirements described above, the students worked on the second part of the course, the intended planning of which is summarised in Table 2. As can be seen from the table, the course planning required the students to first use the requirements as a main driver to the definition of the configuration and the sizing of the platform, in terms of endurance, take-off weight *etc.*. Having established the main configuration parameters, the students then moved to the detailed design, focusing on the mechanical and electrical aspects, placing of the components and wiring. Subse-

Activity	Duration (h)
Platform sizing	2
Platform design	3
Component testing and characterisation	4
Platform simulation model and tool	2
Control oriented models	2
Platform integration and characterisation	4
Control law tuning	4
Test-bed verification	2
In-flight verification	2
Preparation of final report	4
Preparation of final presentation	4

Table 2. Student activities with planned durations.

quently, following acquisition of the components for the construction of the multirotors, the students carried out the mechanical, electrical and electronic integration tasks and proceeded to the characterisation of the propulsion subsystems and the calibration of the simulation model (see the following section for further details). In the actual implementation of the planning in Table 2, however, inte-

gration activities turned out to be significantly more time-consuming than anticipated, so that test-bed verification was skipped and controller setup had to be reduced to simple in-flight tuning based on empirical rules, prior to the execution of the final endurance tests to validate the designs against the initial requirements.

The final tasks carried out by the student teams consisted in the preparation of a design report and of a presentation of the results, followed by a technical discussion.

Following the complete integration of the platforms it was possible to verify compliance with the original requirements. The results in terms of TOW and endurance showed that the designed multirotors are compliant with the original requirements (see, again, Giurato et al. (2019) for a detailed presentation of the results).

3. ADVANCED AEROSPACE CONTROL

Automatic control systems play an increasingly important role in aerospace engineering, both in view of the higher level of automation expected from flight vehicles and of the recent emergence of unmanned vehicles. In particular, control systems design problems in aerospace pose significant challenges because of their intrinsically multivariable, nonlinear nature, often associated with large model uncertainty and unstable dynamics. These are the main reasons why advanced methods for analysis and synthesis are frequently adopted in aerospace applications. In view of the above, the Advanced Aerospace Control course has the following objectives: to provide a sound background on modern methods and tools for the stability and performance analysis of linear and nonlinear systems; to cover robust analysis and design of SISO and MIMO linear time-invariant (LTI) feedback control systems; to discuss basic ideas on the linear parameter-varying (LPV) framework for gain-scheduled control systems design; to present classical results on nonlinear analysis; to illustrate the above methods using detailed case studies. In greater detail, the syllabus of the course, which has a duration of about 60 hours, can be summarised as follows:

- Introduction: motivation for advanced analysis and design methods and introductory examples.
- Systems theory - stability: Lyapunov stability analysis for equilibria of nonlinear systems; stability analysis for LTI systems using Lyapunov inequalities and equations.
- Systems theory - performance: H_2 performance for linear systems; small gain and passivity theory; H_∞ performance for linear systems.
- Linear SISO feedback systems - robust analysis and design: uncertainty modelling in SISO systems; robust stability analysis of SISO feedback systems; nominal and robust performance analysis; requirement specification; robust design unstructured and structured mixed sensitivity synthesis.
- Linear MIMO robust analysis and design: introduction to MIMO linear systems; nominal stability and performance in the MIMO case; robust stability and performance in the MIMO case; MIMO robust design.
- Nonlinear analysis methods: Static nonlinearities: circle and Popov criteria; Limit cycles and oscillations: the describing function method; Introduction to non-

linear design: feedback linearisation, backstepping, adaptive control.

- Case studies: attitude control for a small-scale UAV; attitude control for a full-scale helicopter.

As can be seen from the above items the course is intended by design to be fundamental in character, so as to allow students to be able to understand more advanced analysis and design methods throughout their careers. To compensate for the theoretical emphasis of the lectures, the exam for the course is organised in the form of a project, which allows the students to turn theory into practice and eventually see their design solutions fly in the FlyART laboratory. More precisely, the course has been given yearly since the Academic Year 2016/17 and the design problems posed to the students were defined as follows:

- AY 2016/17: robust control design of a single axis of attitude control for a quadrotor.
- AY 2017/18: robust control design of a single axis of position control for a quadrotor with a suspended load.
- AY 2018/19: decoupling of roll and pitch dynamics and multivariable robust stability analysis for a coupled multirotor.

In the following, some details about the 2018/19 problem statement will be provided, as well as an illustration of a design solution provided by one of the student teams. The project aimed at studying coupled roll/pitch attitude control for a multirotor platform which exhibits an inter-axis coupling which is significant in magnitude and highly uncertain.

As an example, consider the time histories of position and velocity in the North-East-Down (NED) frame following the application of a 1-meter step change in the North set-point, depicted in Figure 3; while one would expect a pure North response without deviations, the roll/pitch coupling in the dynamics causes a small deviation in the East direction. The interaction is even more visible when looking at attitude responses, Figure 4, which how the drone rolling while a pure pitch response would be expected.

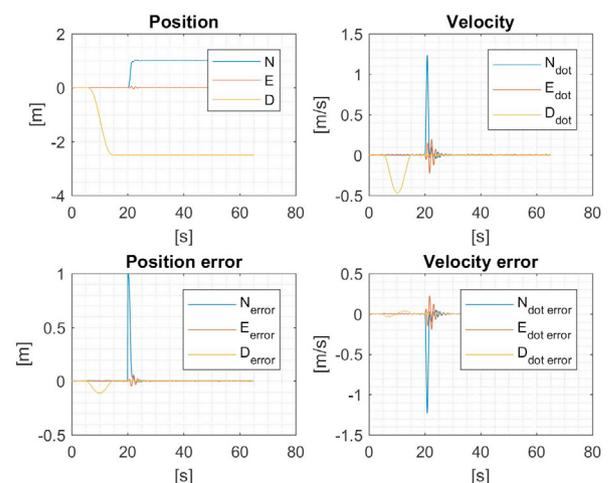


Fig. 3. Position response of the coupled quadrotor to a step-wise change in the North set-point.

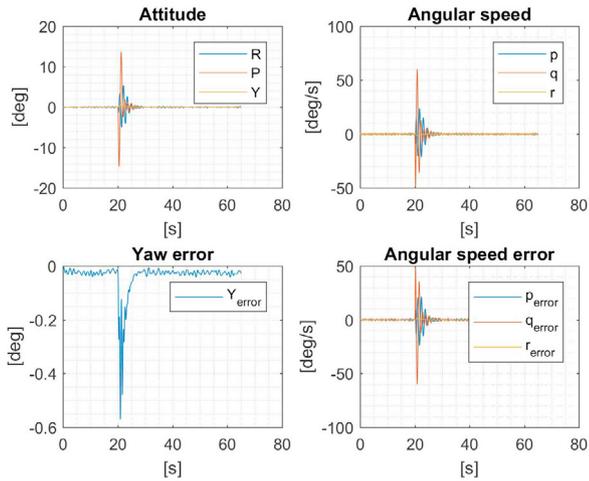


Fig. 4. Attitude response of the coupled quadrotor to a step-wise change in the North set-point.

Even though real quadrotors rarely exhibit such issues due to the intrinsic symmetry of the configuration, such couplings are typical of conventional helicopters, which motivates the study of a decoupling problem within a rotorcraft attitude control framework. For practical purposes, on the real platform the coupling was introduced *via* software, by simply rotating by a suitably chosen angle the pitching and rolling moments applied by the control system. Uncertainty was introduced by perturbing the angle with respect to the nominal value. Step responses and Bode plots of the uncertain linearised model are shown in Figure 5 and Figure 6.

To study the problem, the following inputs were provided to the students:

- A nonlinear simulation model (Simulink) for the complete dynamics of the coupled quadrotor.
- A nominal MIMO linearised model for the pitch/roll dynamics and set of perturbed models corresponding to different values of the coupling angle.
- A description of current attitude controller structure (MIMO but with diagonal gains).

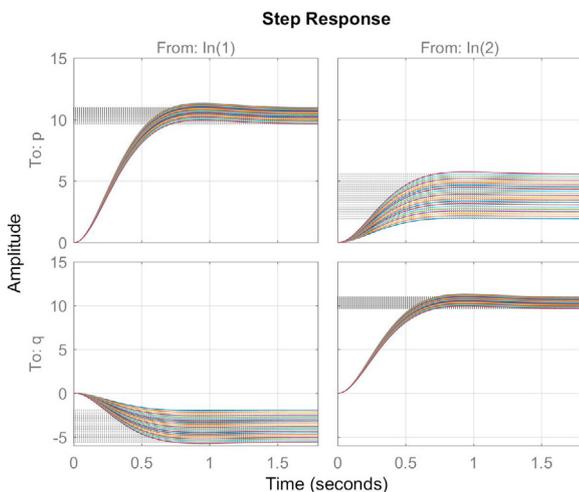


Fig. 5. Step responses of the uncertain linearised model.

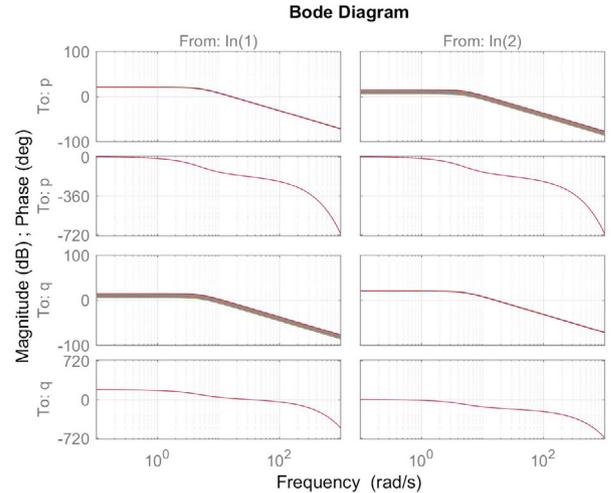


Fig. 6. Bode plots of the uncertain linearised model.

The following performance requirements had to be fulfilled:

- Nominal attitude tracking and inter-axis decoupling.
- Robust stability of the coupled pitch/roll dynamics with respect to model uncertainty.

And finally the following outputs were expected:

- Presentation of adopted design approach and design results
- Quantitative performance verification on an assigned benchmark
- In-flight validation.

All student teams were able to achieve the required design goals. Specifically, the design of the pitch/roll decoupler turned out to be very simple, in view of the way in which the coupling was introduced in the plant model. Subsequently, the robust stability analysis taking into account the discrepancy between the non-nominal coupled plants and the nominal decoupler was carried out in terms of the maximum singular value of the $M-\Delta$ decomposition of the uncertain feedback system. As an example, we report in Figure 7 the plot of the maximum singular value for the uncertain plant obtained by one of the student teams.

Finally, the obtained designs were tested in flight, by executing step responses in the North direction consistent with the simulations reported in Figure 4. The results are reported in Figure 8 and Figure 9, which show the time histories of the pitch and roll rates respectively without and with decoupling.

4. CONCLUSIONS

In this paper, an outline of the UAV Lab multirotor design and integration course and of the Advanced Aerospace control course has been presented and discussed. As described in the previous sections, the first course emphasizes hands-on experience with respect to conventional lectures, leveraging the available competences of the students and the multidisciplinary nature of the teams, while the second uses experimental work to support the theoretical treatment of topics in robust and nonlinear control. The

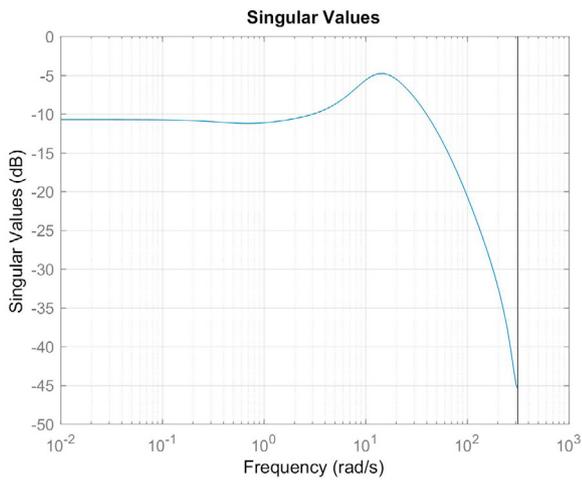


Fig. 7. Maximum singular value for the uncertain plant.

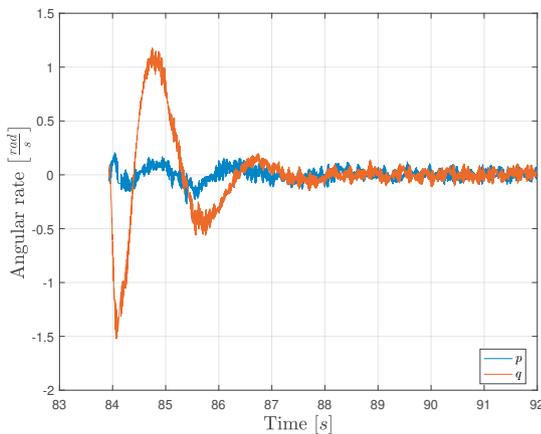


Fig. 8. Closed-loop angular rate response - before decoupling.

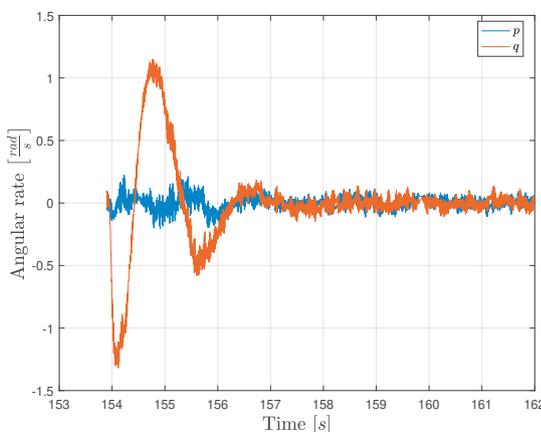


Fig. 9. Closed-loop angular rate response - after decoupling.

experience of the first iteration of the UAV Lab course has been extremely positive from the students' point of view, both in terms of direct feedback to the instructors and in terms of evaluations gathered anonymously through suitable forms. In particular, the design and built multirotors are now being used for research activities within FLYART. In this respect the UAV Lab course turned

out to be an effective form of synergy between education and research. Similarly, for Advanced Aerospace Control the design projects and the related laboratory verification provide simple and effective means to match the theoretical study of robust and nonlinear control with hands-on experience.

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