# UAV Lab: a multidisciplinary UAV design course

**Mattia Giurato** [*] **Paolo Gattazzo** [*] **Marco Lovera** [*]

[*] *Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, Via La Masa 34, 20156, Milano, Italy (e-mail: marco.lovera@polimi.it).*

---

**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 of the UAV Lab course, held at Politecnico for the first time in the fall of 2018, is presented and discussed. The course, aimed at an interdisciplinary group of students, 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. The course has been conceived as an extra-curricular activity, 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. The paper presents the course syllabus and organisation and provides an overview of the obtained results and the feedback provided by the students.

---

## 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 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 of the UAV Lab course, held at Politecnico di Milano for the first time in the fall of 2018, is presented and discussed. The 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 sections, 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.

The paper is organized as follows. The approach to the organisation of the course is presented in Section 2 and the corresponding syllabus is discussed in Section 3. Subsequently, the sizing approach used by the student teams to carry out the conceptual design activities and the three requirement specifications provided to the student teams are then illustrated in Section 4, while an overview of the students' design activities and an example of the obtained results (referring specifically to one of the designed multirotors) are provided, respectively, in Section 5 and in Section 6. Finally Section 7 provides a discussion of the overall course experience, some lessons learned and a few perspectives for further developments.

## 2. APPROACH

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

- a call for the definition of three interdisciplinary teams was sent to Master students in Aeronautical Engineering, Space Engineering, Computer Science and Engineering, Automation and Control Engineering. These four Master programs were selected among the ones offered at 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, so as 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 (see Section 4 for details).
- Subsequently, three design specifications to be implemented by the students were presented in detail and students were allocated to corresponding interdisciplinary design teams.
- Each of the teams carried out a preliminary design, using the methods and tools presented in the initial

part of the course. Such designs were subsequently reviewed by the instructors.
- Detailed designs were then carried out, mainly by the student teams, with some feedback from the instructors. The outputs of the detailed designs, corresponding to CAD drawings of the multirotors and corresponding bills of materials, were then subjected to reviews.
- 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).
- Experimental characterisation of the platforms: in the design of multirotor UAVs most of the modelling uncertainty is associated with the propulsion subsystem (Electronic Speed Controllers (ESCs), motors and propellers) so dedicated data-collection experiments were carried out to characterise such subsystems (see Section 6) for details.
- Customisation of multirotor simulation: the numerical values of the parameters obtained from the previous activity were used to customise a general-purpose MATLAB/Simulink simulation model for multirotor UAVs to suit each of the three 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. Finally, endurance tests were carried out to compare actual to required performance.

The course activities have taken place in the Politecnico di Milano Flying Arena for Rotorcraft Technologies (Fly-ART, see Figure 1), a facility which has been designed to support research and education activities in the field of multirotor UAVs, both for single platforms and formations, 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.

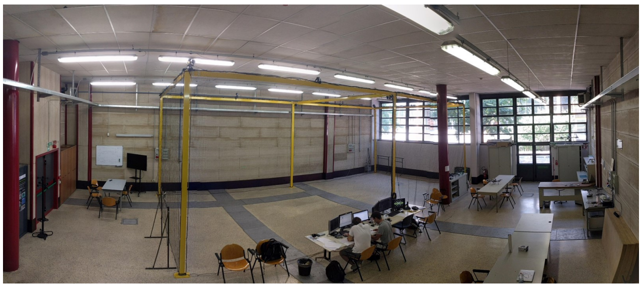

Fig. 1. The FlyART facility at Politecnico di Milano.

## 3. SYLLABUS FOR INTRODUCTORY LECTURES

The introductory lectures mentioned in the previous section were aimed at providing the students an appropriate common ground on multirotor UAVs, their principles of operation, architecture and main characteristics from the point of view of preliminary design. In detail, the following topics were covered (see also Table 1):

- Course introduction and overview of multirotor UAVs: the first lectures were aimed at providing some basic information about the organisation of the course and, mostly, a general overview of multirotor UAVs, in terms of basic principles of operation, dynamic modelling (rigid body, motors, propellers), simulation, model identification and 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 (see Section 4 for details) 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.

## 4. QUADROTOR DESIGN

### *4.1 Design approach*

The design approach used in the framework of the UAV Lab course is very simple and is based on the following considerations and assumptions. 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 high level requirements for Maximum Take-Off Weight (MTOW) and endurance (*i.e.*, flight time).
- Translate the high level requirements to physical quantities, *i.e.*, maximum thrust and energy.
- Select the components of the UAV in order to satisfy the given requirements in terms of thrust and energy.
- Verify by analysis that the solution is feasible and close to the initial requirements.

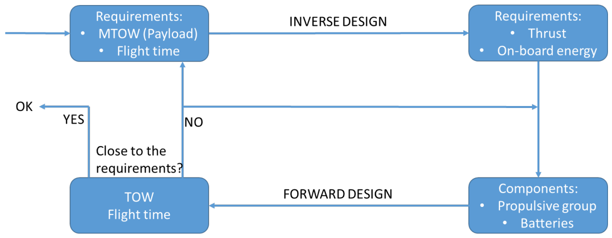

Fig. 2. Block diagram of the design approach.

### *4.2 Design requirements*

The students were divided in three teams, making sure that each group had the required mutidisciplinary character aimed for from the outset of the initiative. Three sets of design requirements were then provided to the students. 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)).

The problem of air-to-air refuelling is well-known and can 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 the overwhelming majority of them has 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, specifically 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 summarised in Table 2 and in Table 3 were formulated.

| **Parameter** | **Value** |
|---|---|
| TOW | As light as possible |
| Flight time | $> 15min$ |
| Landing pad size | $> xxm^2$ |
| Payload | $> 1kg$ |

Table 2. Design requirements for the carrier multirotor.

| **Parameter** | **Value** |
|---|---|
| TOW | $0.6kg < \text{TOW} < 0.8kg$ |
| Flight time | $> 10min$ |
| Frame size | $250mm$ |
| Payload | FPV camera and video antenna |

Table 3. Design requirements for the lander multirotor.

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 tiltable 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, summarised in Table 4 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.

| **Parameter** | **Value** |
|---|---|
| TOW | $0.4kg < \text{TOW} < 1kg$ |
| Flight time | $> 10min$ |
| Thrust-to-weight ratio | $> 3$ |
| Payload | Tilting mechanism treated as payload |

Table 4. Design requirements for the tiltrotor UAV.

## 5. STUDENT DESIGN ACTIVITIES

Starting from the lectures described in Section 3 and the design approach and requirements outlined in Section 4, the students worked on the second part of the course, the intended planning of which is summarised in Table 5. 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. Subsequently, following acquisition of the components for the construction

| **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 5. Student activities with planned durations.

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 5, however, integration 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.

## 6. OBTAINED RESULTS

In this section the results obtained by the UAV Lab students are presented and discussed, with specific reference to one of the three teams, for the sake of conciseness. More precisely, the focus will be on the design of the lander drone, starting from the requirements listed in Table 3. Using the sizing approach outlined in Section 4, the lander team was able to work out a sizing and a set of components compatible with the required MTOW and endurance. For validation purposes, the obtained solution was analysed using eCalc; the results of the eCalc analysis in terms of range and endurance, reported in Figure 3, were fully consistent with the preliminary sizing.

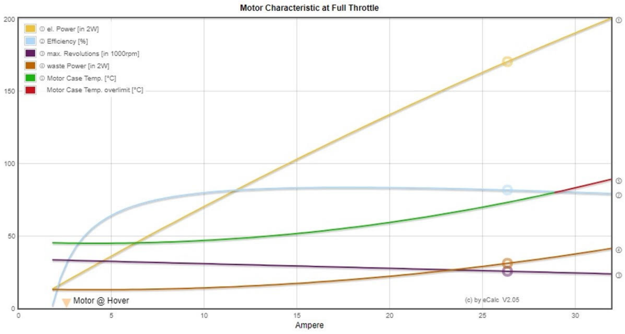

Fig. 3. Performance characteristics of the final design for the lander.

The CAD drawing of the designed lander multirotor is depicted in Figure 4. Following the integration of the propulsive subsystems, their characterisation was carried out using the setup illustrated in Figure 5, which was already available within the laboratory. The setup allows to measure the thrust and the angular rate produced by the propeller, so as to collect data such as the ones depicted in Figure 6 and Figure 7 for, respectively, the $\omega$ vs throttle and thrust vs $\omega$ characteristics, where $\omega$ is the propeller angular rate. The same figures also report linear and quadratic models obtained from the two datasets. Such models, together with inertial properties derived from CAD drawings, were then used to tune a general-purpose MATLAB/Simulink quadrotor simulation model which was provided to the students.

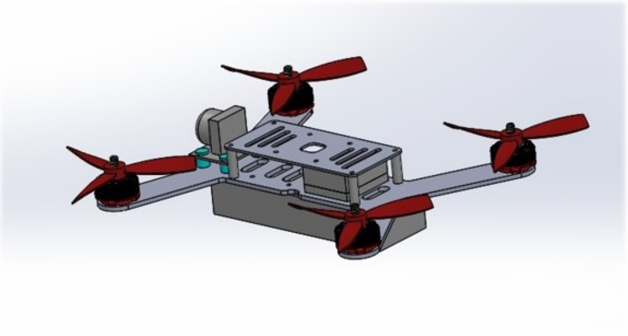

Fig. 4. CAD drawing of the lander multirotor.

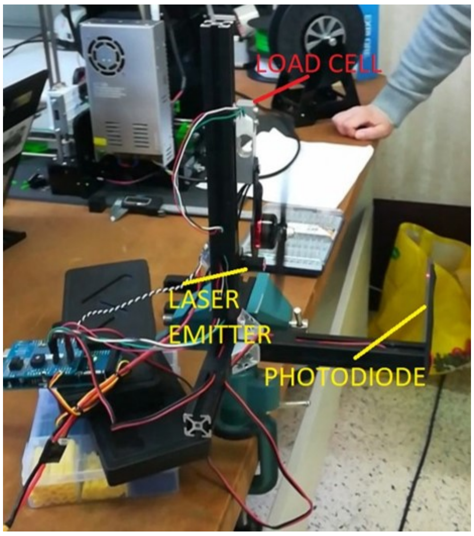

Fig. 5. Setup for drive system characterisation.

Finally, following the complete integration of the platform (see Figure 8) it was possible to verify compliance with the original requirements. Besides TOW, which is easily checked, to verify the expected performance in terms of hover endurance dedicated tests were carried out. The results in terms of TOW and endurance are reported in Table 6, from which it can be seen that the designed multirotor is compliant with the original requirements. Finally, time histories of the measured attitude and position (under feedback control) during the endurance tests are depicted in Figure 9 and Figure 10. As can be seen, even though limited time was available for the tuning of the attitude and position control loops, accurate pointing and positioning were achieved.

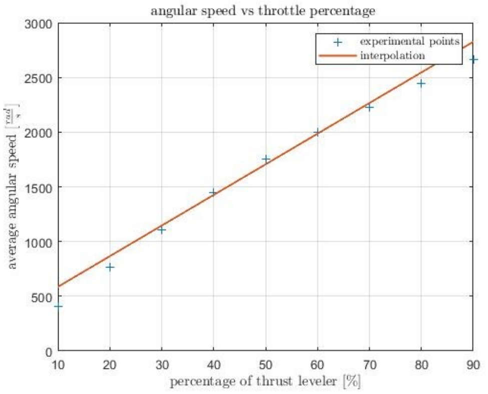

Fig. 6. Drive system characterisation: $\omega$ vs throttle.

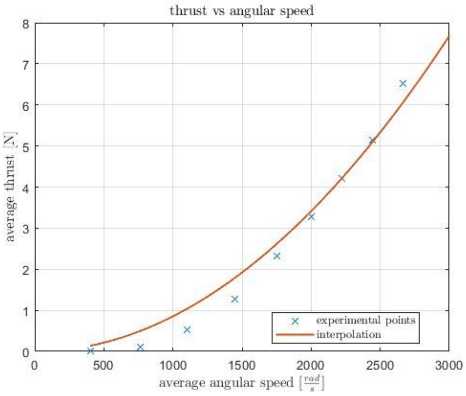

Fig. 7. Drive system characterisation: thrust vs $\omega$.

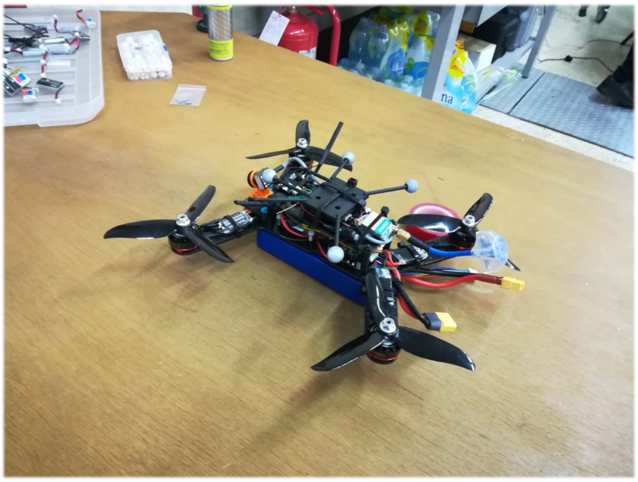

Fig. 8. The integrated lander UAV.

| **Parameter** | **Requirement** | **Design** | **Result** |
|---|---|---|---|
| TOW | $0.6kg < \text{TOW} < 0.8kg$ | $0.683kg$ | $0.734kg$ |
| Flight time | $> 10min$ | $10.5min$ | $13.3min$ |
| Frame size | $250mm$ | $250mm$ | $250mm$ |

Table 6. Design requirements, design results and experimental results.

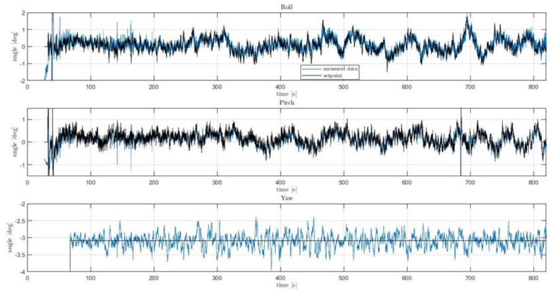

Fig. 9. Hover control performance: attitude errors.

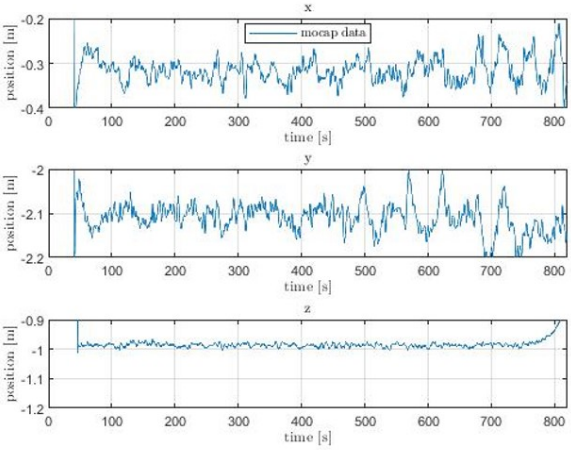

Fig. 10. Hover control performance: position control.

## 7. CONCLUSIONS

In this paper, an outline of the UAV Lab multirotor design and integration course has been presented and discussed. As described in the previous sections, the course emphasized hands-on experience with respect to conventional lectures, leveraging the available competences of the students and the multidisciplinary nature of the teams.

The experience of the first iteration on this 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.

For future iterations of the course the schedule will be revised to take into account the past experience, namely the very time-consuming nature of integration activities, the original planning of which did not consider to a sufficient extent the students' learning curve in this task. Indeed this went to the detriment of the foreseen activities in control design, which had to be reduced to fit the overall schedule.

## 8. ACKNOWLEDGEMENTS

The Authors would like to thank the students who participated in the course for their enthusiasm and passion.

This paper is dedicated to the memory of one our students, Pietro Rapini, who passed away suddenly in December 2018.

# REFERENCES

Brescianini, D. and D'Andrea, R. (2016). Design, modeling and control of an omni-directional aerial vehicle. In *Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, 3261–3266. doi:10.1109/ICRA.2016.7487497.

Crowther, B., Lanzon, A., Maya-Gonzalez, M., and Langkamp, D. (2011). Kinematic analysis and control design for a nonplanar multirotor vehicle. *Journal of Guidance, Control, and Dynamics*, 34(4), 1157–1171.

Gaponov, I. and Razinkova, A. (2012). Quadcopter design and implementation as a multidisciplinary engineering course. In *IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE)*.

Giuri, P., Marini Cossetti, A., Giurato, M., and Lovera, M. (2019). Air-to-air automatic landing for multirotor UAVs. In *5th CEAS Conference on Guidance, Navigation and Control, Milano, Italy*.

Invernizzi, D., Giurato, M., Gattazzo, P., and Lovera, M. (2018). Full pose tracking for a tilt-arm quadrotor UAV. In *Proc. IEEE Conf. Control Technology and Applications (CCTA)*, 159–164. doi: 10.1109/CCTA.2018.8511566.

Invernizzi, D. and Lovera, M. (2018). Trajectory tracking control of thrust vectoring UAVs. *Automatica*, 95, 180–186.

Kastelan, D., Konz, M., and Rudolph, J. (2015). Fully actuated tricopter with pilot-supporting control. *IFAC-PapersOnLine*, 48(9), 79–84.

Khan, S., Jaffery, M.H., Hanif, A., and Asif, M.R. (2017). Teaching tool for a control systems laboratory using a quadrotor as plant in MATLAB. *IEEE Transactions on Education*, 60(4), 249–256.

Rajappa, S., Ryll, M., Bülthoff, H.H., and Franchi, A. (2015). Modeling, control and design optimization for a fully-actuated hexarotor aerial vehicle with tilted propellers. In *2015 IEEE International Conference on Robotics and Automation*, 4006–4013. IEEE.

Ryll, M., Bülthoff, H.H., and Robuffo Giordano, P. (2015). A novel overactuated quadrotor unmanned aerial vehicle: Modeling, control, and experimental validation. *IEEE Transactions on Control Systems Technology*, 23(2), 540–556.

Solution for All Markus Mueller (2019). eCalc. `https://www.ecalc.ch/`.