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Integration of experimental activities into remote teaching using a quadrotor test-bed

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Abstract: The role of laboratory activities in engineering education is fundamental to enhance the students engagement and learning. In this paper we discuss the use of a laboratory test-bed for education and research developed to replicate the dynamic behavior and the control design challenges of an underactuated multirotor Unmanned Aerial Vehicle (UAV), which is becoming a game-changing technology in several application fields. In view of recent challenges related to online teaching activities, the setup has been endowed with a remotization kit to allow students to access the system from anywhere with an internet connection and to perform experiments with satisfactory results. The experience gathered in integrating laboratory activities with the proposed test-bed into the undergraduate Control Systems module at Imperial College London is reported. The paper presents the development and organization of the remote laboratory lectures and provides an overview of the obtained results.

1. INTRODUCTION

It is well known that education in science and engineering can significantly benefit from practical experimentation. While laboratories activities have been used to complement theoretical lectures in various fields for quite some time, providing a valuable experience in the context of aerospace engineering is challenging for a combination of reasons, from availability of limited resources to space and safety obstacles.

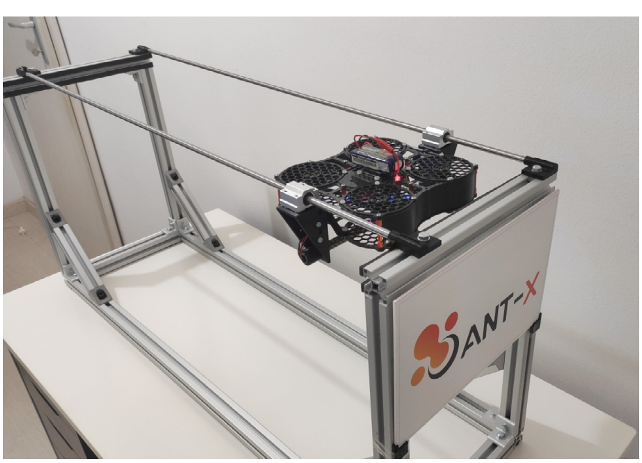

Fig. 1. The ANT-X 2DoF Drone.

A marked turn has been represented by the advent of small-scale Unmanned Aerial Vehicles (UAVs), which have become widespread in many fields with new applications emerging every day. Besides being interesting platforms on their own, they provide a unique test-bed for validating general flight control concepts in a effective and affordable way (Giurato et al., 2019). Education activities involving the design of UAVs and the related problems in guidance, navigation and control are offered more and more often in recent years, with courses covering both specific design and operation aspects (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); Giurato et al. (2020); Castaldi and Mimmo (2019); Hong et al. (2019)).

In this paper, we discuss the use and integration into laboratory activities of a test-bed, the ANT-X 2DoF Drone, developed by a spin-off company of Politecnico di Milano (ANT-X, 2020). Based on a quadrotor UAV fixed to a structure that allows only the longitudinal motion, it is intended to provide students with hands-on experiences in the design and validation of flight control laws. Leveraging a dedicated software to automatically generate and integrate controllers developed in Simulink into the drone firmware, the ANT-X 2DoF Drone can be directly commanded from MATLAB, relieving students focused on control design aspects from coding implementation issues. On

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the other hand, being based on an open-source firmware PX4 (2020) fully customizable by the users, it can also be used as a platform for advanced research studies. While in the companion paper Panza et al. (2021) the conceptual design and the dynamic characterization of the ANT-X 2DoF Drone are discussed, in this work we focus on the development of educational material to support teaching activities. After presenting several didactic experiments, we report the experience gathered in using the ANT-X 2DoF Drone within the undergraduate Control Systems module at Imperial College London, placing emphasis on the integration into the course theoretical lectures and the organization of the experimental activities, which had to be performed remotely due to contingent Covid-19 situation. In this regard, ANT-X 2DoF Drone has been equipped with a remotization kit, designed to allow the users experiencing the laboratory setup even remotely with satisfactory results.

2. THE ANT-X 2DOF DRONE

In this section we briefly introduced the ANT-X 2DoF Drone. For a thorough description of the system and a dynamic characterization of the platform, the readers are referred to the companion paper (Panza et al., 2021). A video showing the main features of the platform and its capabilities is available at https://youtu.be/ttkqtivycCs.

2.1 Dynamical model

The ANT-X 2DoF Drone has been designed to replicate the longitudinal motion in near-hovering flight conditions when the multirotor dynamics can be approximated by four decoupled sets of differential equations describing, respectively, the yaw, the altitude, the pitch/x-translation and roll/y-translation dynamics (Ghignoni et al., 2021). Specifically, the linearized longitudinal dynamics is described by:

$$\dot{\theta} = q \qquad J_\theta \dot{q} = M_c + M_e \tag{1}$$

$$\dot{x} = v_x, \qquad m\dot{v}_x = -mg\theta + f_e \tag{2}$$

where (θ, q) are the pitch angle and rate, respectively, (x, v) are the position and velocity along the x-axis, respectively, m is the quadrotor mass, J_θ is the pitch inertia moment, $g = 9.81 m/s^2$ is the gravity acceleration while M_e, f_e are torque and force disturbances. While the pitch dynamics (1) is actuated by M_c, the translational motion (2) can be controlled only indirectly, by changing the pitch angle. The longitudinal dynamics (1)-(2) captures the relevant challenges of the underactuated dynamics of co-planar multirotor UAVs, which is an appealing feature from the educational point of view.

2.2 System description

The ANT-X 2DoF Drone test-bed comprises three main components:

- the drone: a fully functional quadrotor with additional features to operate in safety: the propellers are contained within the frame and protected on multiple sides so that they do not come in contact with external objects;
- the main structure: made up of an aluminum frame and two steel bars which constrain the translational motion of the drone through a cart with linear ball bearings;
- the ground control station: the computer from which the user interacts with the drone. It can be the user's laptop or any computer properly configured with the necessary software.

There are two operational modes for the drone:

- *attitude mode (1 DoF)*: by constraining the linear displacement DoF through removable mechanical constraints (1DoF rings), the drone is free to rotate about the pitch axis alone;
- *position mode (2 DoFs)*: in this operating mode, the drone is left free to move along the bars, giving two DoFs (translation and rotation).

2.3 Software architecture

The 2DoF Drone is based on open-source software; in particular, it is based on PX4, an open source flight stack for drones, widely used in academia and industry, and on ROS, a distributed operating system providing communication infrastructure and the possibility to implement high level applications.

Two proprietary software tools have been developed by ANT-X. The SLXtoPX4 tool allows to automatically integrate attitude and position controllers, designed in Simulink and customizable by the user, into the PX4 firmware. Completely transparent to the user, this tool does not require programming skills and allows the user to focus on the design of control laws. This functionality is especially useful in courses devoted to the understanding of principles of automatic control, allowing students to focus on the development of control laws without having to deal with low level implementation issues. At the same time, the PX4 firmware, being an open-source software, can be directly modified by advanced users for more complex implementations or in courses more focused on coding/software architecture design activities.

The DroneCmd tool is a MATLAB API which provides the capability to communicate with the drone, send commands, and receive information. It allows to carry out experiments on the 2DoF Drone (for instance, to test controllers by sending setpoints on attitude, angular rate, position, ...), to get telemetry feedback and to log experimental data. Both these proprietary software tools have been developed in the MATLAB/Simulink environment. Finally, the 2DoF Drone can be operated remotely by means of remote access (see paper Panza et al. (2021) for details).

3. DEVELOPMENT OF EDUCATIONAL MATERIAL

A set of experiments complemented with educational materials (slides and documents) has been prepared to support teaching activities in the design of flight control laws. The possibility of doing repeatable experiments in safety conditions allows one to perform simple identification tests and to experimentally validate the modeling stage, which gives a relevant value to the educational experience. After an introductory lecture to familiarize with the ANT-X 2DoF Drone through a "Hello World"-like hands-on example, the rest of the material is organized in four lectures, briefly outlined below.

3.1 Angular rate dynamics model identification (1DoF).

The objective of this lecture is to obtain a sufficiently accurate model describing the pitch motion of the ANT-X 2DoF Drone when the translational degree of freedom is constrained (more details about the identification procedures can be found in the companion paper Panza et al. (2021)). A time-domain identification technique is proposed based on the following second order model:

$$G_q(s) = \frac{\mu s}{s^2 + 2\xi\omega_n s + \omega_n^2} e^{-\tau s} = \frac{q}{M_c^d} \tag{3}$$

where ω_n is the natural frequency, ξ the damping ratio and μ the gain. The transfer function in (3) is derived from equation (1) and by collapsing all unmodelled dynamics (sensors, actuators) and delays (computational processing, digital implementation) into the lumped term $e^{-\tau s}$. The identification problem is then split in three subproblems which require performing two experiments:

- by inspecting the response of the system to an impulse-like input and by measuring the oscillation period T_p and settling time T_s, the parameters ω_n and ξ can be estimated by using the approximated formulae $\omega_n \approx \frac{2\pi}{T_p}$ and $\xi \approx \frac{4.6}{T_s \omega_n}$;
- by applying a doublet signal input, under the linearity assumption, the gain μ can be estimated as the ratio between the peak of the response obtained in the experiment with the one simulated using the identified values of ω_n and ξ.

Finally, the time delay τ can be estimated by visual inspection of the response or by using the Matlab *delayest*() routine on the collected data. The time-domain verification of the identified model can be seen in Figure 2.

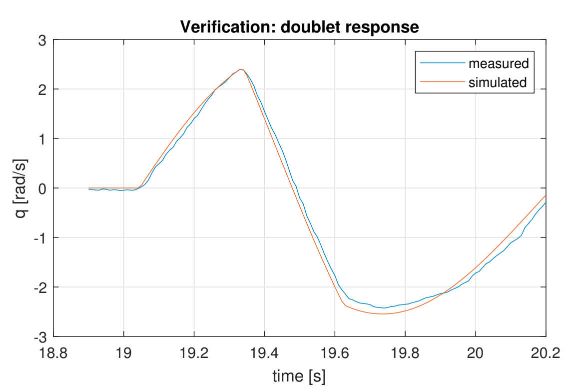

Fig. 2. Experimental verification of the identified pitch rate model.

3.2 Angular rate control (1DoF)

Starting from the identified model in (3), the objective of this lecture is to tune and implement a PID controller for the pitch rate dynamics using the control moment M_c^d as input:

$$M_c^d(s) = \left(K_p + K_i \tfrac{1}{s} + K_d \tfrac{s}{\tau_f s + 1}\right) e_q(s) \tag{4}$$

where $e_q(s) = q_d - q$, $K_p, K_i, K_d > 0$ are the proportional, integral and derivative gain, respectively, and τ_f is the derivative filter constant. After inviting the users to manually tune the controller to understand the effect on the response of each individual PID gain, a loop-shaping approach is shown to achieve satisfactory robustness and performance guarantees in terms of minimum phase margin and crossover frequency. Since the identified model has two complex-conjugate low frequency poles, the model transfer function is approximated in the desired control bandwidth by $G_q(s) \approx \frac{\mu}{s^2} e^{-s\tau}$ and then, the loop function

$$L_q(s) = PID(s)G_q(s) \approx \frac{\bar{\mu}}{s^2} \frac{(\tau_1 s + 1)(\tau_2 s + 1)e^{-s\tau}}{(\tau_f s + 1)} \tag{5}$$

is shaped according to the following strategy:

- set the derivative filter pole sufficiently at high frequency with respect to the desired crossover frequency ω_c^d;
- place one zero at low frequency $\left(\tau_1 = \frac{10}{\omega_c^d}\right)$ and one beyond ω_c^d $\left(\tau_2 = \frac{1}{2\omega_c^d}\right)$ to cross the $0dB$ axis with $-20dB/dec$ slope;
- select $\mu = \frac{\omega_c^d}{\tau_1}$ in order to cross the $0dB$ axis at the desired crossover frequency (note that $\|L_q(j\omega_c^d)\| \approx \bar{\mu}\tau_1/\omega_c^d$).

The PID gains are then recovered using $K_i = \bar{\mu}/\mu$, $K_p = (\tau_1 + \tau_2)K_i - K_i\tau_f$ and $K_d = \tau_1\tau_2 K_i - K_p\tau_f$. The performance achieved when selecting $\omega_c^d = 30rad/s$ with $\tau_f = 0.01\,\mathrm{s}$ is shown in Figure 3. The users are then encouraged to test different performance requirements and compare the results. The last part of the lecture is devoted to presenting digital implementation strategies and discuss possible issues, such as the effect of reduced sampling rates (Figure 4).

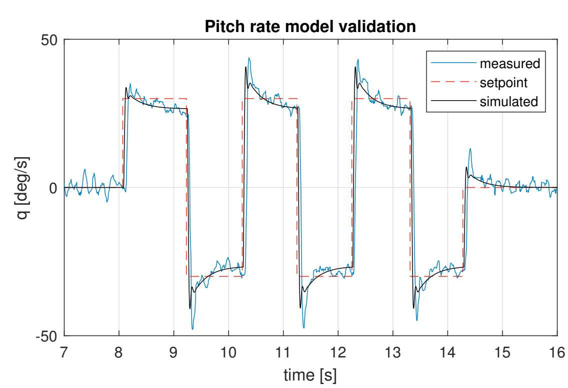

Fig. 3. Simulation vs measured setpoint tracking results for pitch rate control.

3.3 Attitude control (1DoF)

In this lecture we show the design of a cascade control system to achieve desired performance for the pitch attitude dynamics, noting that in the Laplace domain, the system (1) can be written as the cascade

$$\theta(s) = G_\theta(s)q = \tfrac{1}{s}q \tag{6}$$

$$q = G_q(s)M_c^d. \tag{7}$$

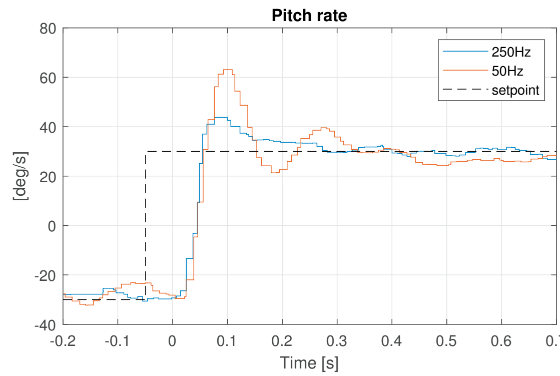

Fig. 4. Effect of sampling rate on pitch rate control.

Assuming that the angular rate controller is tuned in order to achieve adequate performance, a frequency separation argument is proposed to design the outer loop controller using the pitch rate $q = q_d$ as the control variable. Since $G_\theta(s)$ in (6) is a simple integrator, a viable solution, which, incidentally, is adopted by most multirotor autopilots, is to employ a proportional controller for the outer loop, namely,

$$q_d = K_p^o e_\theta = K_p^o(\theta_0 - \theta), \tag{8}$$

where $K_p > 0$ is the proportional gain. The overall strategy (rate and angle control) becomes a cascade P/PID control law (Figure 7). Following a loop shaping tuning approach, we suggest approximating the outer loop transfer function (frequency separation) as

$$L_\theta(s) = K_p^o G_\theta(s) T_q(s) \approx \frac{K_p^o}{s}, \tag{9}$$

where $T_q(s) = L_q(s)/(1 + L_q(s))$ is the complementary sensitivity of the inner loop. The error in adopting such an approximation for control design is shown in Figure 5. To achieve a desired crossover frequency ω_c^d, the value of the gain can be obtained by assigning $|L_\theta(j\omega_c^d)| = 1$, from which one gets $K_p^o = \omega_c^d$, *i.e.*, the proportional gain is set equal to the desired crossover frequency. Several experiments are then proposed according to different tuning requirements and to simulate the effect of a bias on attitude feedback measurements. The performance achieved when setting $\omega_c^d = 11\,\mathrm{rad/s}$ is shown in Figure 6 in terms of the response to a doublet reference.

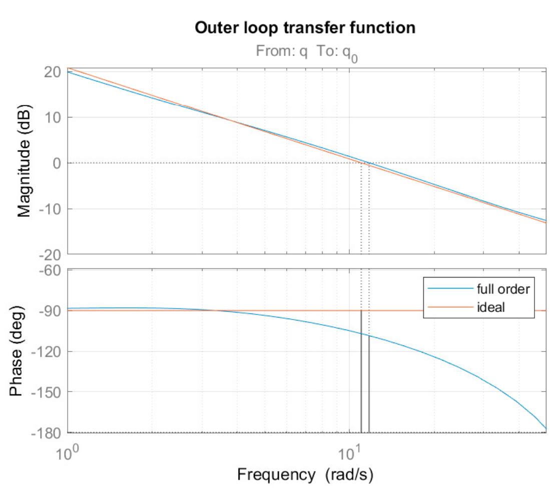

Fig. 5. Comparison between the approximated ($T_q \approx 1$) and full order outer loop functions.

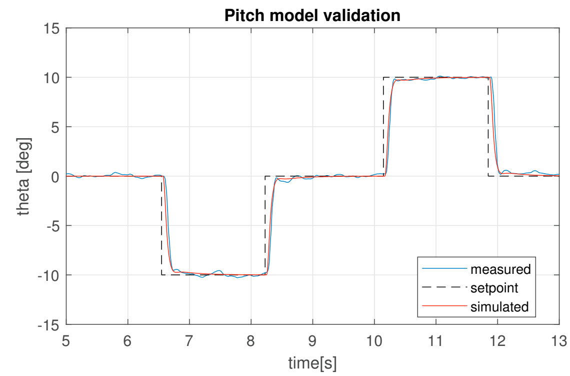

Fig. 6. Simulation vs measured setpoint tracking results for pitch angle control.

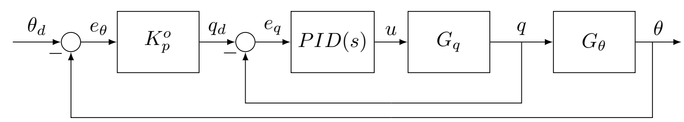

Fig. 7. Cascade scheme for attitude control.

3.4 Position and velocity control (2DoF)

The objectives of the this lecture are: 1) characterize a model of the ANT-X 2DoF Drone translation dynamics using a simple identification procedure and 2) design a position control law dealing with the underactuated nature of quadrotors. The first objective is accomplished by performing a simple experiment to identify the parameters of the velocity dynamics approximated by the first order model

$$v_x(s) = G_v(s)\theta = -\frac{k_v}{s+p_v}\theta \tag{10}$$

which is derived from (2) using a linear friction model (see the companion paper Panza et al. (2021) for additional details). The second objective is achieved by designing a cascaded controller that uses the pitch angle as a virtual input for the position dynamics, which is the standard approach in multirotor control to handle underactuation. Assuming the attitude control system be sufficiently fast, *i.e.*, $\theta_d \approx \theta$ ($T_{att}(s) = L_\theta(s)/(1 + L_\theta(s)) \approx 1$), a loop shaping procedure is presented to tune a P/PID controller (the same structure used for the attitude controller) with a desirable level of robustness and performance. Figure 8 shows the results in terms of set-point tracking corresponding to a tuning achieved by requiring a crossover frequency of 4.5 rad/s) and 1.5 rad/s) for the inner and outer loop, respectively.

4. THE EXPERIENCE AT IMPERIAL COLLEGE LONDON

4.1 The undergraduate Control Systems module

The Control Systems module is a primary level course that aims to introduce transfer-function-based methods for the analysis and design of control systems. The module covers some aspects of dynamical systems modelling and control systems analysis and design. It provides the foundation for specialized study in the control theory and its real-world applications. The module is composed of the theory lectures (see Table 1) and the experiments (see Table 2),

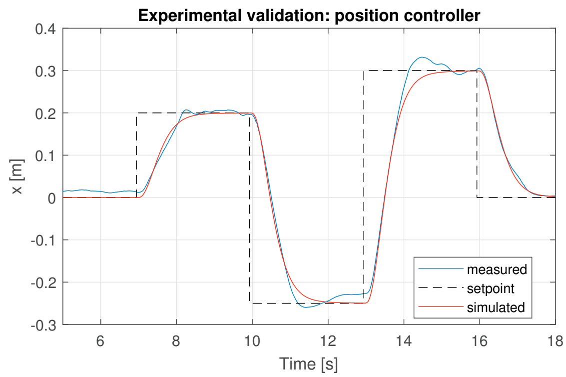

Fig. 8. Experimental validation of position control.

both of which were delivered in parallel online for 11 weeks, from January to March, 2021, during the UK national lockdown due to COVID-19.

Table 1. Syllabus of the lectures

Part	Topics of the lectures
1	Course introduction
2	Fundamentals of system theory
3	Stability
4	Transfer function
5	Block schemes
6	Stability of interconnected systems
7	Step-response analysis
8	Sinusoidal and frequency response
9	Analysis of feedback control systems
10	Design of feedback control systems

Table 2. Schedule for experiments

Week*	Experiments	Mode**
2	Introduction	Hybrid
3	System identification	Remote
4	Angular rate control (simulation)	Remote
5	Angular rate control (implementation)	Hybrid
7	Attitude control (simulation)	Remote
8	Attitude control (implementation)	Hybrid
9	Position control (simulation)	Remote
10	Position control (implementation)	Hybrid

* No experiments were scheduled on Weeks 1, 6, and 11.
** See Section 4.2 for explanations.

The theory lectures introduce the fundamental concepts of system analysis and controller design. More specifically, Parts 4 and 5 of the theory lectures illustrates the transfer-function-based modeling procedures for linear systems. Part 7 provides a systematical method to analyze the step response, which is exploited by the PID gain tuning in the experiments. Parts 8, 9, and 10 of the lectures introduced several frequency-based approaches (*e.g.* the loop shaping method) and related concepts (*e.g.* phase margin and crossover frequency) of controller design for interconnected systems. These concepts are re-addressed by the experiments that provide opportunities for the students to implement the learned theory in a real-world project and help the students develop comprehensive capabilities in control engineering.

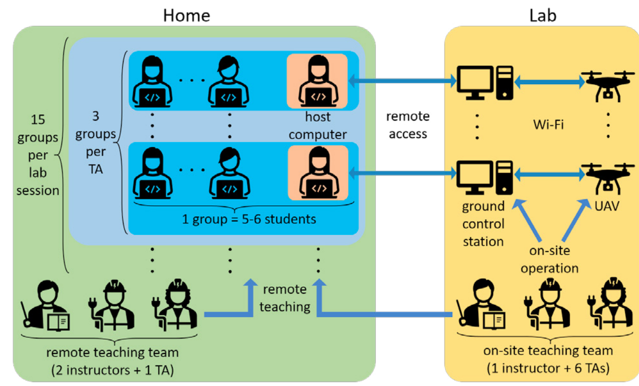

Fig. 9. Schematic of the hybrid-mode lab organization

4.2 Organization of the experimental activity

In the lab sessions, the 176 enrolled students were divided into 30 groups, with 5 to 6 students in each group operating one UAV platform. Two identical 2-hour lab sessions were scheduled each week. Each lab session, led by a teaching team comprised of 3 course instructors and 7 teaching assistants (TAs), accommodated 15 student groups.

To minimize the on-campus activity, two teaching modes, the remote mode and the hybrid mode were adopted for the lab sessions. In the remote-mode sessions, both the students and the teaching team worked from home. The students received course materials before each lab session and worked on control synthesis and simulation verification tasks during the lab session. The groups discussed and cooperated on their tasks via an online meeting software, while the teachers joined their group meetings regularly to answer questions. The hybrid-mode lab sessions exploited the aforementioned remotization of the UAV platform and were divided into a home part and a lab part, running simultaneously, as shown in Figs. 9 and 10. The students of each group worked from home and operated the GCS remotely from a host computer via remote access so that controller tuning and experimental data collection could be completed without the need for on-site attendance. The on-site teaching team consisted of an on-duty instructor and six TAs, who worked on-site in the laboratory providing necessary logistic support (for work that cannot be done remotely, *e.g.* battery replacing and hardware trouble shooting) to the students. The rest of the teaching team worked from home and provided online assistance to the students similarly as in the remote-mode sessions.

After collaboratively collecting the data from each experiment, the students processed and analyzed the data independently. To keep the fairness of assessment, each student were required to submit an individual lab report based on the processed data and a set of questions randomly chosen from a question pool. In the light of this, the final feedback on the lab report was also provided to each student individually.

4.3 Discussions on the effectiveness

The effectiveness of the reported lab organization scheme is analyzed in terms of three pairs of interaction: the

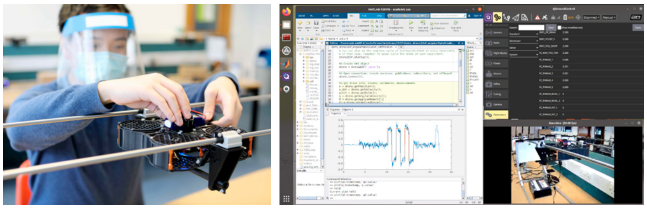

Fig. 10. Demonstration of the hybrid-mode lab. Left: battery replacement by an on-site TA. Right: controller tuning (the upper-right window), experimental data collection (the left window), and real-time UAV monitoring (the lower-right window) by students via remote access

student-student, the student-teacher, and the student-hardware interaction. It was a concern in the beginning of the course that the students would have difficulties in cooperating with each other due to the work-from-home situation. The actual experiences showed that this was not the case as they could discuss even more efficiently than in classical labs because of convenience in sharing files and data via online meeting software (in contrast, in classical labs the files are mostly shared via email). The collaborative operation on the GCS was achieved by switching the host computer or remotely controlling the host computer. The drawback, compared with the classical labs, was that the communication delay of the remote access reduced the efficiency of operation and slowed down the progress, to an extent depending on the quality of network communication.

For the student-teacher interaction, the reported scheme showed its advantage of providing feedback and assessment at an individual level, whereas in the classical organization scheme these are typically made at a group level. There were mainly two reasons for these observations. First, the students appeared to be more comfortable in asking questions or seeking help in private in the remote teaching case, and the teachers tended to leave comments with more details to a specific question from an individual student. Second, in the remote teaching case, the engagement and contributions of each student were automatically documented online, which significantly facilitated the individual assessment. This, in turn, encouraged the students to participate more actively. Some of the students' feedback indicated that the individual-level feedback and assessment of the reported scheme were more helpful than the classical schemes. The downside was, however, that the teachers had to do more logistic work than in the classical labs, which could have be done by the students if they were on site and therefore teachers' efforts to help students were inevitably dispersed.

Regarding the student-hardware interaction, thanks to the online tuning capability of the platform, the students were able to modify the controller settings with minimum intervention from the teaching team. The webcam integrated on the experimental platform also helped the students sense the response of the UAV in an intuitive way, which to some extent compensated for the loss of experience caused by remote teaching. Due to the technological limitations, even the hybrid-mode labs can hardly guarantee a learning experience comparable to that of classical on-site labs. However, considering the infeasibility of on-site teaching due to the lockdown restrictions, the reported scheme still provided much better experience than a simulation-only lab, which was confirmed by some of the students' feedback.

5. CONCLUSIONS

In this paper, the potentialities of a laboratory test-bed based on a multirotor UAV in improving teaching activities have been discussed. The experience of the integration of the ANT-X 2DoF Drone into the laboratory activities of the Control Systems module at Imperial College London has been reported, together with a description of the organization of the experimental activity in an innovative remote mode to comply with lockdown restrictions in UK due to Covid-19.

6. ACKNOWLEDGEMENTS

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