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Design and characterization of the 2DoF Drone: a multirotor platform for education and research

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Abstract: In this paper we present the design of a laboratory test-bed for education and research which is intended to replicate the dynamic behavior and the control design challenges of an underactuated multirotor Unmanned Aerial Vehicle (UAV). The proposed setup is designed to study the longitudinal and pitch dynamics of a multirotor UAV by running experiments in a safe and controlled environment and in a repeatable way. Based on an open-source firmware (PX4), customizable by the user for advanced research implementations, a dedicated software has been developed to implement controllers at high level in Simulink, to automatically generate and integrate the controller code into the firmware and then to command the drone from MATLAB. In view of remote teaching activities, the setup hardware and software allows for an easy remote access that still provides a satisfactory learning experience to the users. Physically motivated identification procedures have been devised to characterize the platform dynamics for didactic purposes and for the use in the design of control laws.

1. INTRODUCTION

In recent years Unmanned Aerial Vehicles (UAVs) have attracted the attention in several application fields, from personal and commercial use to industrial applications. In the context of civil applications, multirotor UAVs are the most common platform, thanks to their agility and reliability. Education activities involving the design of multirotor UAVs and the related problems in guidance, navigation and control have become more and more widespread, with courses covering both design and operation and system-level design issues (see, *e.g.*, Gaponov and Razinkova (2012); Khan et al. (2017); Belyavskyi et al. (2017); Giurato et al. (2019, 2020)).

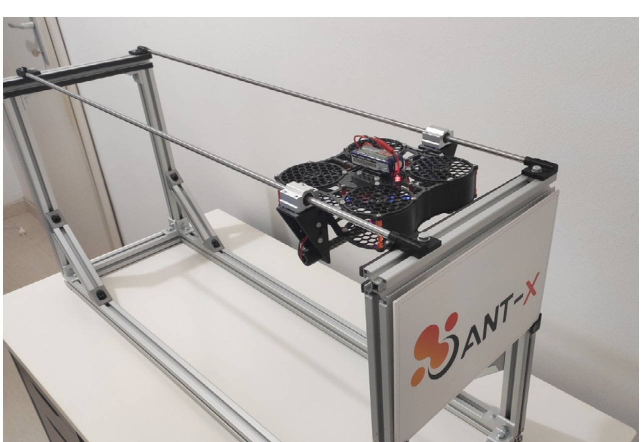

Fig. 1. The ANT-X 2DoF Drone.

In this paper, we present the design of a laboratory test-bed, the ANT-X 2DoF Drone, developed by a spin-off company of Politecnico di Milano (ANT-X, 2020) to be used in aerospace and automatic control education and research activities. Based on a fully operational quadrotor UAV and a suitable structure constraining all the degrees of freedom (DoFs) but the pitch rotation and the longitudinal translation, it is designed to replicate the dynamics of underactuated multirotors and allows students and researchers to design and test flight control laws in an efficient, safe and repeatable way. The software of the drone is based on an open-source firmware PX4 (2020), one of the most adopted autopilots for industrial applications, which is fully customizable by the user for advanced research implementations. For educational purposes in aerospace and automatic control courses, a dedicated software has been developed to let students focus on the development of control laws at high level in Simulink, to automatically generate and integrate the controller code into the drone firmware and then, to command the drone from MATLAB. The ANT-X 2DoF Drone is provided with educational materials to learn in an incremental way control design strategies for multirotor UAVs and to show the challenges of on-board implementation on a real hardware, which are typically only touched-upon topics in theoretical lectures (see the companion paper (Invernizzi et al., 2021)). The test-bed is compact and can be operated and controlled remotely with a real-time camera and suitable software, thereby enabling remote teaching activities.

The identification procedures presented in the work have been developed for educational purposes: that is, starting

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from first-principles models and designing simple identification experiments, data are collected from the experiment and are post-processed using a simple and intuitive method which allows to estimate the model parameters values. In this way, it is possible to involve undergraduate engineering students potentially coming from different courses, with a background on fundamentals of systems and signals as a pre-requirement; it is possible to present the identification problem even to students with no background at all on identification. This is opposed to the approach of using advanced identification methods, which on the one hand could deliver more accurate models, but on the other hand requires a solid background on identification techniques.

The paper is organized as follows. The conceptual design behind the development of the ANT-X 2DoF Drone is presented in Section 2, where the system dynamics and the software architecture are described as well. The kit enabling remote access to the drone is discussed in Section 3, while the characterization of the platform and the identification experiments for both the pitch and the translational dynamics are reported in Section 4.

2. PLATFORM DESIGN

2.1 Conceptual design

The conceptual design behind the ANT-X 2DoF Drone (Figure 1) was the development of a platform suitable for the testing and validation of flight control concepts for multirotor UAVs (*e.g.*, position and attitude controllers design) in a safe and controlled environment and in a repeatable way. The proposed setup has been designed to replicate the longitudinal motion of quadrotors, which is described by the following set of equations:

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

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

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, T_c is the control thrust, M_c is the control torque produced by the differential thrust between fore and aft motors and (2) while M_e, f_e are torque and force disturbances. While the pitch dynamics (1) is fully actuated by M_c, the translational motion can be controlled only by changing the pitch angle (note that for $\theta = 0$, T_c disappears from (2)). Being able to study the longitudinal dynamics (1)-(2) is important since such a dynamics captures all the most relevant challenges related to the underactuated nature of co-planar multirotors. The simplified, yet representative behaviour of the coupled attitude and linear translation dynamics of the drone can be captured by simple models in an effective way, which represents an appealing feature from the educational point of view. Moreover, the possibility of doing repeatable experiments in safety conditions allows to perform simple identification tests and to experimentally validate the modeling stage, which adds further value to the educational experience.

2.2 Description of the system

The ANT-X 2DoF Drone test-bed comprises three main components: the drone, the main structure and the ground control station (which is described in Section 2.3). The ANT-X 2DoF Drone is a quadrotor UAV designed for research and educational purposes. It is a real drone, 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 drone is powered by a LiPo battery.

The structure of the test-bed is 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 lightweight structure can be easily unmounted for storage and can be placed on a desk, requiring limited space (size 100 x 30 x 40 cm). The drone is constrained to the cart vertical supports by means of rotational ball bearings, which allow the rotation about the pitch axis with minimal friction. A laser Time-Of-Flight (TOF) sensor is mounted on the cart and measures the distance of the drone from the end stroke both for safety and state estimation purposes.

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. This mode can be used to study the rotational dynamics (1) and to design single-axis attitude control laws using M_c as input variable.
- position mode (2 DoFs): in this operating mode, the drone is left free to move along the bars, giving two DoFs (translation and rotation). This mode allows addressing the control design for the underactuated but controllable longitudinal dynamics of the drone (1)-(2), where M_c is again the input variable.

A video showing the main features of the platform and its capabilities is available at https://youtu.be/ttkqtivycCs.

2.3 Software architecture

The 2DoF Drone software architecture is distributed across several hardware components:

- *Ground Control Station* (GCS): 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. In case the experimental setup is operated in presence, the user can employ a virtual machine pre-configured with the necessary software to operate the 2DoF Drone. In case the 2DoF Drone is paired to a remotization kit, a miniPC already configured with the software needed to operate the 2DoF Drone is used as a ground station.

- *Flight Control Unit* (FCU): it runs the open-source PX4 firmware on top of a RTOS (Real Time Operating System) onboard the drone. The FCU is meant to run low-level functionality, such as the controller, the estimators, and the sensor modules. It is equipped with an IMU measuring accelerations and angular rates at high frequency. The firmware is customizable by the user; specifically, the user has the possibility to customize the controller at very low level, interfacing directly to the control actions of the single motors.

- *Flight Companion Computer* (FCC): onboard the drone, it runs a Linux distribution, and provides communication to the ground control station via WiFi and to the FCU via serial communication. The user has the possibility to write and run custom high-level applications on the FCC (compared to the low-level control functions running on the FCU), using the ROS infrastructure.

The ANT-X 2DoF Drone software integrates the several open-source and proprietary software packages [1] which are described below.

- *PX4 firmware**: Open-source firmware running on the FCU. The user can customize the position and attitude controllers by means of the SLXtoPX4 software tool (described below), which integrates the user's custom controller developed in Simulink into the firmware.

- *Robot Operating System (ROS)**: ROS is a distributed OS running on multiple machines: distributed across the GCS and the FCC of the drone, ROS provides an infrastructure which enables communication between nodes in the network, which in turn allows to run user applications.

- *MATLAB*** and Simulink***: The former provides the user with an interface to interact with the drone from the GCS; The latter is used to develop custom attitude and position controllers using an intuitive graphical user interface.

- *SLXtoPX4****: Starting from controllers developed in Simulink, the SLXtoPX4 tool automatically generates the controller code and integrates it in the PX4 firmware. Completely transparent to the user, it does not require programming skills and allows the user to focus on the design of control laws.

- *DroneCmd****: Application Programming Interface (API) to interact with the drone from MATLAB. It is used for: sending setpoint commands; receiving onboard estimates/measurements; sending excitation signals (*e.g.*, for identification experiments and validation of controller performance).

- *QGroundControl**: Open-source software providing full flight control and mission planning for drones. It provides real-time telemetry and allows changing firmware parameters online: the user can set up tunable parameters in the custom controller, and modify them in flight using QGroundControl.

2.4 Communication and logging

The software architecture exploits the communication capabilities provided by the ROS infrastructure. Communication between the FCU and the FCC occurs over serial connection, using the MAVLink open-source protocol and a MAVROS node. Communication between the GCS and the drone occurs via WiFi; the WiFi connection is provided by the FCC, which is set up in Access Point mode. The GCS connects to the WiFi network created by the FCC. This allows for a distributed architecture: no router is needed, and multiple 2DoF Drones can be operated simultaneously and independently of each other, since each one will have a dedicated WiFi network.

Flight data are logged directly on the ground control station, exploiting the ROS infrastructure, and are made available to the user in MATLAB format for easy processing. Log data include measurements, estimates and control actions collected onboard the drone and transmitted to the ground control station.

[1] * Open-source; ** third-party proprietary; ***ANT-X proprietary software.

3. REMOTIZATION

The ANT-X 2DoF Drone can be equipped with a remotization kit, designed to allow the users experiencing the laboratory setup even remotely, thereby enabling remote teaching activities. Thanks to the remotization kit the user, equipped with an internet connection, can connect to the 2DoF Drone and run experiments without the need to be physically present in the place where the machine is located.

The development of a remotization kit was motivated by the lockdown restrictions imposed by the outbreak of the COVID-19 pandemy: in order to guarantee that students could have access to the laboratory equipment, it was necessary to devise a way to deliver the laboratory experience remotely. Even after the pandemic emergency will have come to an end, remote laboratory access could still play an important role in guaranteeing access to laboratory equipment to those users who cannot physically be present in the laboratory, *e.g.*, due to geographical reasons (living far from the laboratory facility, or even in another country).

The remotization kit is made up of a ground station, which acts as an interface to the drone, and one camera standing on a support mounted to the frame of the 2DoF Drone. The user is able to connect to the ground station remotely through the Internet, to send commands to the drone, and to receive telemetry feedback and data logged during experiments. The software needed to run the 2DoF Drone entirely runs on the ground station. The user connects remotely using a remote desktop access application, thus needing no software installation on the user's side. The webcam provides the user with visual feedback of the outcome of the experiment. It is remarked that, when using the 2DoF Drone remotely, the user can operate the platform in the same way as it would be done in presence, thus representing a truly experimental remote experience.

It should be noticed that the remote operation of the platform is not completely automated: indeed, the physical presence of at least a human operator is needed in the laboratory, in order to carry out manual operations such as battery replacement, plugging and unplugging the battery, and connecting the programming cable to the drone when needed. As a future development, the possibility to make the 2DoF Drone fully autonomous, with no human intervention at all, is under consideration. This would allow operating the experimental setup 24/7, with considerable benefits both for the institution hosting the laboratory (with no need to necessarily have lab staff in presence) and for the users (who could connect anytime to the platform).

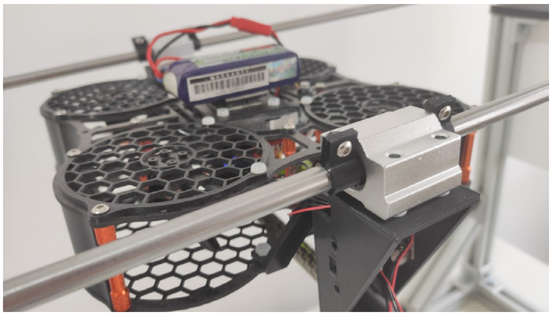

Fig. 2. ANT-X 2DoF drone set-up in 1DoF mode.

4. CHARACTERIZATION OF THE PLATFORM

In this section, the procedure used to characterize the dynamic behavior of the platform is presented. The characterization procedure is aimed at obtaining simple yet accurate models of the relevant dynamics of the platform, to be used for control design purposes, namely:

- a model of the angular rate dynamics of the drone in 1DoF mode;
- a model of the linear velocity dynamics of the drone in 2DoF mode.

4.1 Identification of angular rate dynamics

In this section the procedure to obtain an identified model of the angular rate dynamics is explained. The experiment is carried out on the ANT-X 2DoF drone set-up in 1DoF mode (Figure 2). In this configuration the drone is blocked along the bars, and it can only rotate about the pitch axis. The drone constrained in 1DoF mode can be considered as a damped pendulum rotating about the shaft at the rotary ball bearings, *i.e.*, the pitch dynamics can be written as

$$J_\theta \ddot{\theta} = -cq - k\theta + M_c \tag{3}$$

where we used $M_e = -cq - k\theta$ in (1). For control design purposes, the control torque produced by the rotors can be modeled as pure delay with gain:

$$M_c(s) = \eta e^{-\tau s} M_c^d(s) \tag{4}$$

where M_c^d is a normalized input variable, η is the actuator gain and τ collects delays associated with the actuator dynamics, computational delays, digital-to-analog conversion, *etc.*. The transfer function for the angular rate dynamics can then be written from (3) as

$$G_q(s) = \frac{q}{M_c^d} = \frac{\mu s}{s^2 + 2\xi\omega_n s + \omega_n^2} e^{-\tau s}, \tag{5}$$

where ξ is the damping ratio, ω_n is the natural frequency and μ is the gain:

$$c = \frac{2\xi\omega_n}{J_\theta}, \quad k = \frac{\omega_n^2}{J_\theta}, \quad \mu = \frac{\eta}{J_\theta}. \tag{6}$$

The identification problem boils down to the estimation of the four parameters $(\xi, \omega_n, \tau, \mu)$ in (5) and is carried out by considering two experiments in sequence.

Experiment 1: identification of free response parameters. This experiment aims at identifying the parameters of the free response of the open-loop system. An excitation signal similar to an impulse (a constant input with amplitude 0.1 and duration 0.2s, and equal to zero elsewhere) is applied to the pitch control input u, in order to drive the system sufficiently far away from the equilibrium and to impart an initial condition to it. Then, the angular rate of the system is measured (Figure 3). A significant advantage of this method is that the excitation signal and the response are repeatable.

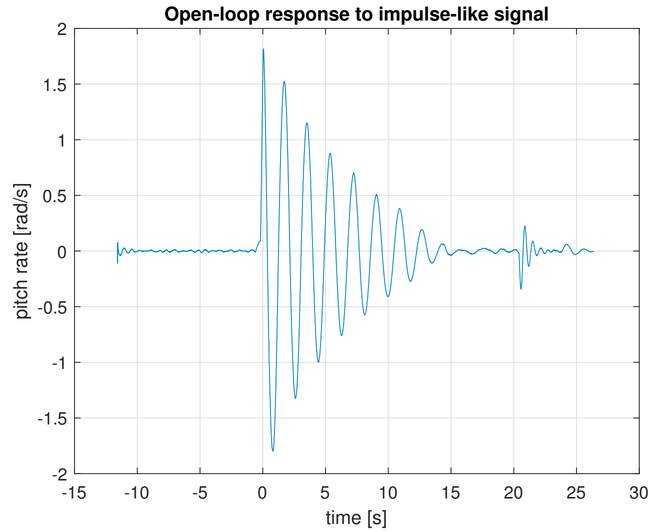

Fig. 3. Angular rate model identification: response to the impulse-like signal.

Assuming the observed response belongs to a second order underdamped system, we can estimate the natural frequency and damping ratio based on the measured oscillation period ($T_P = 1.83\,\text{s}$) and the settling time ($T_S = 16\,\text{s}$):

$$T_P = \frac{2\pi}{\omega_n\sqrt{1-\xi^2}} \simeq \frac{2\pi}{\omega_n} \rightarrow \omega_n = \frac{2\pi}{T_P} \simeq 3.437\,\text{rad/s} \tag{7}$$

$$T_S \simeq \frac{4.6}{\xi\omega_n} \rightarrow \xi = \frac{4.6}{T_S\omega_n} \simeq 0.0836. \tag{8}$$

Experiment 2: identification of forced response parameters This experiment is carried out in open-loop conditions, with no angular rate, nor attitude control loops active. Using linearity arguments, the gain μ can be estimated by simulating the response with the same excitation signal used in the experiment and comparing the peak of the simulated response to the peak of the measured response. The considered excitation signal is a doublet signal with period 0.6 s and amplitude 0.03. It is worth remarking that the amplitude shall be large enough for the signal-to-noise ratio to be reasonable and to sufficiently excite the vehicle dynamics, but not so large that the amplitude of the motion exceeds the physical limits of the test-bed (the attitude angle shall not exceed 50deg or the drone will hit the carbon rod). For the same reason, the period of the doublet shall not be overly large. Also, it is advisable to excite the system at a sufficiently large frequency with respect to the natural frequency to avoid resonance.

The plot of the input and output signals logged in the experiment are shown in Figure 4. The experiment was repeated three times so that one dataset is used for identification and verification, and other datasets are available for validation. The positive peak of the measured response (Figure 4) is $y_{PK} = 2.40\,\text{rad/s}$ while the peak of the simulated response obtained using $\mu = 1$ is $y_{PK}^{SIM} = 6.68 \times 10^{-3}\,\text{rad/s}$. Then, μ can then be estimated as $\mu = \frac{y_{PK}}{y_{PK}^{SIM}} \simeq 358.5$. Finally, the equivalent time delay $\tau = 20\,\text{ms}$

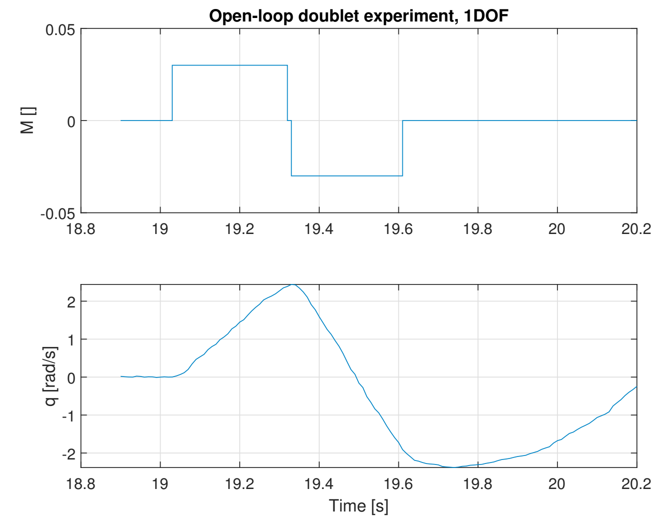

Fig. 4. Experimental data: angular rate identification dataset.

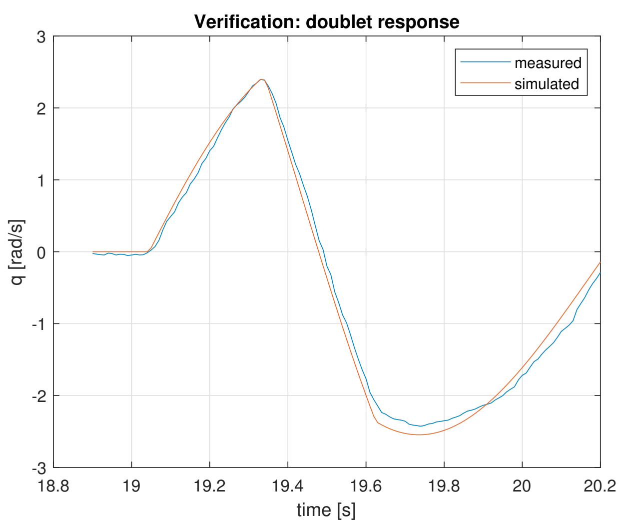

Fig. 5. Angular rate model: verification.

was estimated inspecting logged data by measuring how many time samples pass between the moment in which the input is applied and the output starts moving.

Verification and validation Figure 5 shows verification results, comparing the measured response to the simulated one. The initial response is accurately captured; the doublet excitation frequency is $\frac{2\pi}{0.6} \simeq 10.5\,\text{rad/s}$ which is above the natural frequency and close to the intended attitude rate control bandwidth frequency range. The low frequency response content, associated with the pendulum dynamics, is not correctly captured but this is not a big issue as far as control design is concerned, in that this frequency interval will be well below the attitude rate control loop bandwidth.

4.2 Identification of linear velocity dynamics

The objective of this experiment is to obtain a model of the velocity dynamics of the ANT-X 2DoF Drone in the 2DoF mode, which is described by:

$$m\dot{v}_x = -T_c \sin(\theta) - c_v v_x, \tag{9}$$

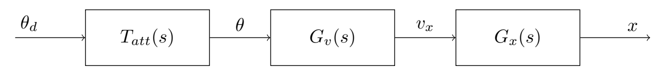

Fig. 6. Block diagram of the cascaded attitude and translation dynamics model.

where we assumed in (2) a linear friction along the bars, *i.e.*, $f_e = -c_v v_x$, with c_v being the friction coefficient, and where m includes both the drone and the cart mass. Assuming that an attitude controller guaranteeing good performance for setpoint tracking is available, the desired pitch angle θ_d can be considered as an input to the velocity dynamics. Keeping constant the thrust during the experiments ($T_c = \bar{T}_c$) and assuming small angles, $\sin(\theta) \approx \theta$, the transfer function relating the input and the translational velocity is $G_v(s) = \frac{v_x}{\theta} = -\frac{k_v}{s+p_v}$, which is a first order system depending on the parameters k_v and p_v. The overall dynamics is represented in Figure 6, where the left block $T_{att}(s)$ represents the closed-loop attitude dynamics, while the central and right blocks $G_v(s)$ and $G_x(s) = 1/s$ represent the translation dynamics, and are forced by the pitch angle θ. Note that in deriving (9), static friction between the ball bearings and the steel bars has been neglected. This imposes to operate with large enough pitch angles and velocities in order to excite the system far enough from the equilibrium point of zero speed.

Experiment design. Based on the previous section, the problem of designing the experiment to estimate the parameters k_v and p_v thus reduces to choosing a proper pitch angle setpoint signal θ_d. A suitable signal for the purposes of this experiment, is a doublet signal, which is characterized by an amplitude A and a period T_D.

The doublet signal parameters should be chosen keeping into account the following considerations:

- the amplitude of the θ_d doublet should be large enough to produce a force sufficient to overcome the static friction;
- the period of the doublet should be large enough to excite the velocity dynamics, that is, to let the drone move along the bars and accelerate until reaching a sufficiently large velocity; moreover, the dynamics of the closed-loop attitude response should be taken into account as well in determining the doublet period, supposing that the attitude response is fast enough, although non instantaneous;
- at the same time, it should be kept into account that the stroke of the bars of the 2DoF Drone is limited, allowing for an effective displacement of approximately 80 cm from end to end. Thus, the speed and displacement of the drone shall be limited, in order to avoid hitting the end strokes. This in turn implies that both the amplitude and the period of the doublet shall be limited in magnitude.

The following ranges of parameters are suggested:

- amplitude A between 10 deg and 20 deg;
- half-period between 0.6 s and 1 s, resulting in a period T_D between 1.2 s and 2 s.

As an example, Figure 7 shows the experimental results for a doublet of amplitude 15 deg and half-period 0.8 s; the top half of the figure shows the pitch angle setpoint

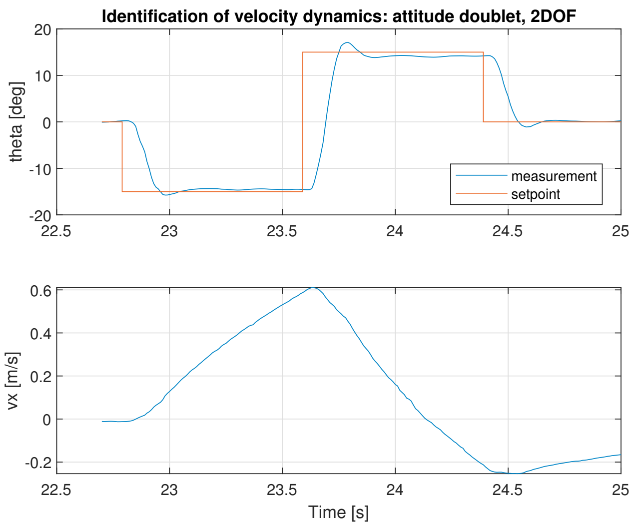

Fig. 7. Velocity model identification experiment: pitch angle and velocity responses.

Table 1. Velocity model identification: numerical results.

Variable	Unit	Our method	greyest
k_v	m/s^2	4.041	4.748
p_v	s^{-1}	0.7387	1.168

signal and the pitch angle response, while the bottom half shows the velocity response.

Identification procedure and results. Based on the experimental logged data, the procedure briefly outlined in the following is proposed to estimate the parameters of the model:

- the initial acceleration $\hat{a}_{x,I}$ is estimated by computing the slope of the velocity plot in the initial part of the experiment;
- the parameter k_v is estimated as $k_v = -\frac{\hat{a}_{x,I}}{\bar{\theta}}$ where $\bar{\theta}$ is the amplitude of the pitch angle doublet;
- the parameter p_v is estimated exploiting the analytic expression of the step response of a first order system, assuming for simplicity that the closed-loop attitude dynamics are much faster with respect to the velocity dynamics.

A more refined model can be obtained by means of advanced identification methods. In particular, the MATLAB greyest routine was used which implements a grey-box identification procedure based on the output error method, either in the frequency domain or in the time domain. Table 1 reports the estimated values of the parameters obtained with greyest, comparing them to the values obtained with the proposed method. In particular, the damping ratio seems to be underestimated by our method, compared to greyest.

Figure 8 shows verification results, comparing the performance of the model obtained with our method to the model obtained with greyest. In general, the model obtained with greyest captures more accurately the first part of the response, up to the velocity peak.

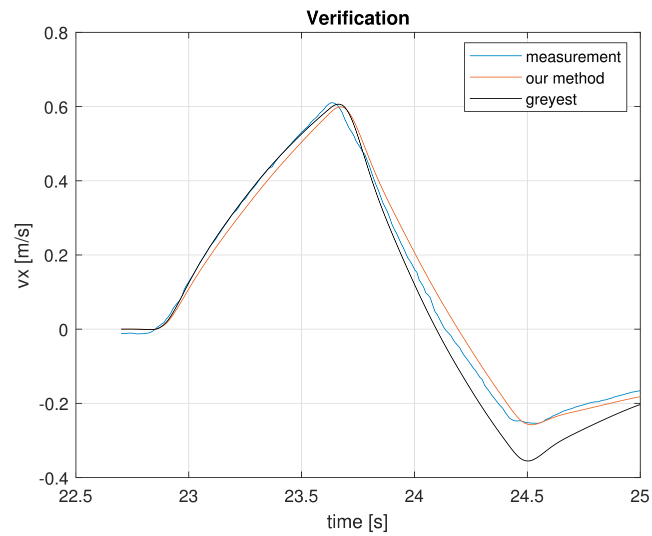

Fig. 8. Velocity model identification: verification and comparison between different methods.

5. CONCLUSIONS

In this paper, the design of a laboratory test-bed for testing flight control laws has been presented and discussed. The platform has been described in details from the conceptual design to the software architecture. The platform has been characterized through simple identification experiments that could be used in courses to obtain simple models suitable for designing control laws.

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