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Bachelor's Final Projects: Integrating Multidisciplinary Learning via Multi-rotor Testbench Design ⋆

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Abstract: This paper presents the outcomes of two thesis projects conducted by bachelor students in Mechatronics Engineering at the University of Padova. The aim of both projects is to design, develop, implement, and validate laboratory testbenches for characterizing key inertial and actuation parameters of small and medium-sized multi-rotor platforms. By integrating concepts from mechanics, electronics, computer engineering, and automatic control, these activities foster a multidisciplinary understanding of mechatronics engineering. Additionally, the practical nature of the projects reinforces comprehension and real-world application of control theory while enhancing teamwork and communication skills.

Keywords: Project-based education, Laboratory equipment, Flight dynamics

1. INTRODUCTION

Mechatronics is a relatively modern branch of engineering with its foundational principles rooted in mechanics and electronics. However, what distinguishes mechatronics is its interdisciplinary nature, where 'mecha' accounts for the widest aspects of the physical embodiments of mechanical engineering, while 'tronics' incorporates all aspects of microelectronics and information technology, including also control and computer engineering (Acar and Parkin (1996)). This fact is evident in mechatronics' objective to integrate modern sensor technology, electronic actuators, and electric drives into electromechanical systems controlled in real-time by programmable electronic devices. The mechatronic systems characterize multiple fields and application domains ranging from the medical field to the automation, manufacturing, robotics and automotive industries (Marzano et al. (2019)).

From an educational perspective, Habib (2007, 2008) argues that the structure of a Mechatronics Engineering Degree program should prioritize comprehensive multidisciplinary knowledge. This can be achieved by incorporating foundational subjects such as physics, mathematics, and statistics, as well as essential topics in computer systems and programming, mechanics, electrical engineering, and electronics. The program of Bachelor of Mechatronics Engineering (B.M.E.) offered by the University of Padova aligns with this paradigm, aiming to educate engineers with a robust technical foundation in mechanical, electrical and information engineering. The curriculum is designed to provide students with the skills necessary to conceptualize, design, develop, and validate mechatronic systems. This includes a broad spectrum of courses ranging from theoretical subjects such as mathematical analysis, algebra, geometry, and general physics, to more specialized topics like fundamentals of mechanics applied to machines and electrical drives, computer science and automatic controls, analog electronics and theory of digital circuits.

As reported by Alatalo et al. (2024), then, hands-on learning is widely recognized as an essential component of mechatronics education. In particular, Habib et al. (2021) emphasizes the role of experiential learning to maximize student engagement and comprehension of theoretical concepts, while also stimulating their creative and critical thinking skills. Guided by these principles, students enrolled in the B.M.E. program at the University of Padova actively engage in practical experiences within the Industrial Computer Laboratory, Electronics Laboratory, and Electrical Drives Laboratory. In the same spirit, students have been recently provided with the opportunity to undertake their final exam (3 CFU, corresponding to expected 75 workload hours) in the form of a collaborative project that involves the design, development, implementation, and validation of real-world mechatronic systems. These thesis projects are designed to offer students first-hand experience in multidisciplinarity, necessitating the integration of mechanical, electrical, and information engineering principles. Moreover, these projects are tailored for students to apply theoretical knowledge to practical problems, while also exposing them to a team-based learning approach that fosters developing soft-skills like attitude to teamwork, communication, and project management.

In this work, we present two B.M.E. final projects in which the mechatronic systems under examination are testbenches for multi-rotor aerial platforms. Both projects

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involve the same autonomous collaborative student working modalities, principal sub-tasks (STs), and verification methods. In detail, we describe the cases wherein the students were tasked with realizing a laboratory testbench to identify the inertial parameters of small and medium-sized multi-rotors (*Project A*), and another laboratory testbench to characterize the capabilities of multi-rotor actuators in terms of the force and torque exerted by propellers (*Project B*). The assignment of *Project A* and *Project B* is motivated by several reasons. From an educational standpoint, the multi-rotor testbenches serve as appropriate mechatronic devices, integrating mechanical, electronic and information engineering aspects without necessitating specialized knowledge in aerospace field. From an academic perspective, designing and implementing laboratory facilities provide a beneficial stimulus for students because their efforts are not solely for their own benefit but contribute to enhancing the future capabilities of the laboratory itself, thus promoting research.

In Section 2, we outline the framework of the projects, emphasizing the skills and knowledge required for the various STs. In Section 3, we detail the realization of these STs in both Project A and Project B. In Section 4, we discuss the educational advantages stemming from these hands-on activities and the positive impact of offering them at the conclusion of the B.M.E. program.

2. FINAL PROJECTS FRAMEWORK

The B.M.E. thesis projects are structured as collaborative activities for groups of three or four students. This enables students to leverage each other's strengths and expertise, while also refining their communication and organizational skills and increasing their sense of responsibility. The realization of the project STs, indeed, needs to be planned and achieved based on group agreement.

Project A and *Project B* encompass the same key STs, starting with the study and comprehension of the mechatronic system fitting the project specifications (**ST0**). In this preliminary phase, the students are tasked to understand the theoretical notions involved in the project and to investigate the existing solutions in terms of strategies and devices. The design of multi-rotor testbenches involves understanding the physical principles governing the dynamics of rigid bodies acting in 3D space, which model the multi-rotor platforms. Additionally, it entails a thorough understanding of the operational principles of their actuation systems, in particular the brushless motors that power the propellers.

ST0 is followed by the conceptualization of the testbench, by accounting for its hardware and software parts. The design of the hardware part (**ST1**) of the testbench involves the sizing of the device, the selection of materials, and mechanical and electrical components, ensuring compatibility and efficiency. In doing so, students are required to apply the knowledge gathered in their mechanics and electronics courses. The design of the software component (**ST2**), on the other hand, is grounded in computer science courses, as it entails selecting appropriate software tools and programming languages for the development of control algorithms and data acquisition and analysis software.

Once ST1 and ST2 are completed, students can proceed to the mechatronic prototype construction and refinement (**ST3**) and to the implementation of necessary algorithms to control the hardware system and collect and interpret the data for performance evaluation (**ST4**). These two STs, which can be performed concurrently, entail iterative improvements based on testing and feedback.

Following the implementation phase, students can focus on system validation (**ST5**), conducting rigorous tests to ensure functionality and reliability. If critical issues emerge in the proposed solution, possible remedies are to be explored to address the problems.

Throughout all the steps, students are tasked to document their progresses and findings, concluding in the preparation of comprehensive technical documentation (**ST6**).

At the conclusion of the projects (typically after 3 months), students have to present their findings and outcomes in a 20/30-minutes presentation which serves as the verification method and constitutes the last step of B.M.E. final exam. The presentation must be equally divided among the group members in terms of both time and content. Students should clearly state their individual contributions to the project, which is also periodically monitored by the tutors through regular update meetings. Based on the presentation and the monitoring, a final individual evaluation (out of 30) is provided.

3. MULTI-ROTOR TESTBENCH DESIGN

In the following, we aim at emphasizing the multidisciplinary nature of the thesis projects by providing detailed descriptions of the STs introduced in Section 2.

3.1 Project A

Motivated by the need of identifying the moment of inertia (MoI) of a multi-rotor for the accurate design of attitude controllers, *Project A* focuses on developing a device aimed at estimating the MoIs of a small-sized multi-rotor platform. To achieve this goal, a group of four students was tasked with constructing a multi-wire pendulum equipped with a sensor capable of measuring the oscillation period of its tray. Additionally, the students were required to implement a procedure for analyzing collected data and subsequently estimating the MoIs of the aerial platform.

ST0: at the beginning, the students focused on the study of experimental estimation techniques based on periodic motion oscillations (Genta and Delprete (1994)). In this direction, for a trifilar pendulum, it is known that the oscillation period $T \in \mathbb{R}_{>0}$ of the tray carrying the test object can be approximated in case of small rotations as

$$T = 2\pi\sqrt{\frac{J\ell}{mgd^2}} \quad (1)$$

where $J \in \mathbb{R}_{>0}$ is the sum of the MoI of the tray (J_0) and of the test object (J_1), $\ell \in \mathbb{R}_{>0}$ is the length of the cables, $m \in \mathbb{R}_{>0}$ is the sum of the mass of the tray (m_0) and the body under investigation (m_1), $g \in \mathbb{R}_{>0}$ is the gravitational constant, $d \in \mathbb{R}_{>0}$ is the distance between the tray center of gravity and the cables connection point (Previati (2021)). Care must be exerted to ensure that the wires have the same length and that

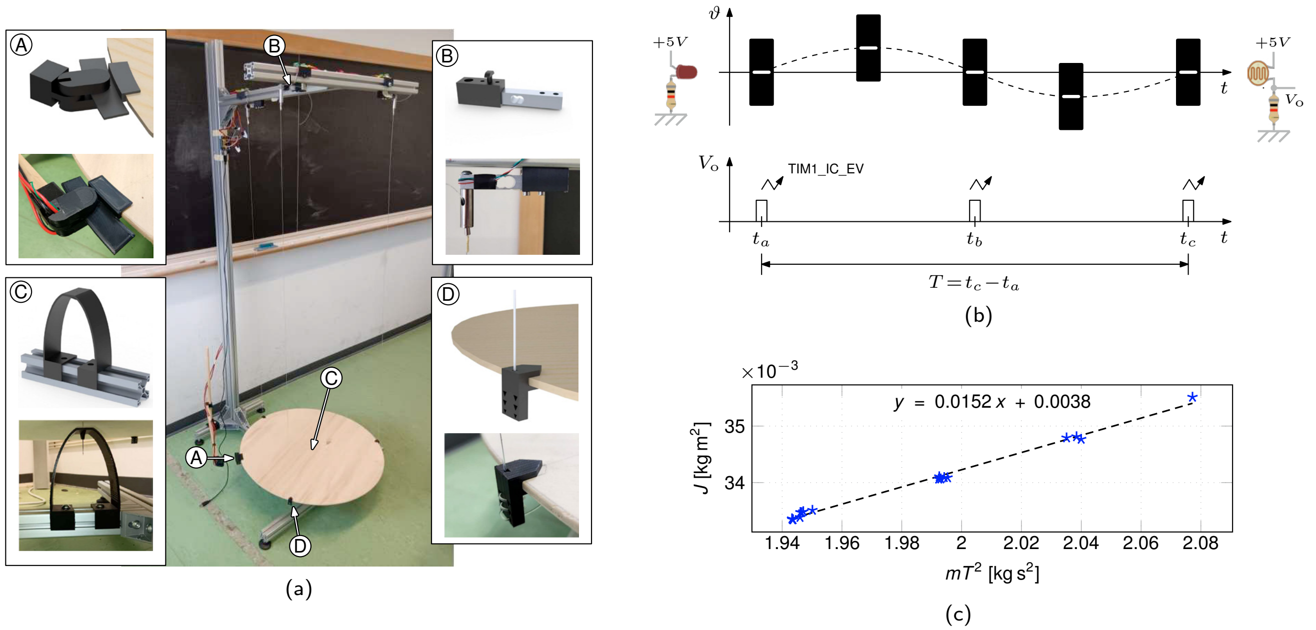


Fig. 1. *Project A*: (a) final prototype of the trifilar pendulum; (b) oscillation period measurement principle; (c) determination of the calibration curve by linear regression.

the center of gravity of the test object is positioned on the rotational axis of the tray. In light of this fact, three sub-objectives are involved in *Project A*: the measurement of the weight of the multi-rotor under investigation and triangulation of its center of gravity, the measurement of the oscillation period of the supporting disk, and the consequent estimation of the multi-rotor MoIs.

ST1: from the mechanical point of view, a trifilar pendulum is composed of three main elements, i.e., the disk-shaped tray, the cables, and the supporting structure. To size them, the students considered a Holybro QAV 250 as the test object. This is a quadrotor with a mass equal to 2 kg, which can be approximated as a box of size 0.4 m × 0.4 m × 0.1 m. Then, to minimize J_0, it was decided to make the tray out of poplar plywood with a thickness of 4 mm, selecting a diameter of 0.65 mm. The resulting MoI is reported in Table 1, along with the other dimensions of the designed trifilar pendulum. Nylon wire with a thickness of 1mm was chosen for the cables, while 40 mm × 40 mm and 40 mm × 80 mm aluminum profiles was selected to build the supporting structure. The cables were connected to the tray by means of three special hooks positioned at equally separated locations along its border. The hooks were designed to allow an easy adjustment and equalization of the cable lengths, as required for the correct operation of the pendulum. An additional support was envisaged to constrain the tray to rotate around its center, so to eliminate the undesired lateral movements.

From an electronic standpoint, three 1 kg load cells were installed on the anchoring points of the cables on the supporting structure, to infer both the weight of the multi-rotor under investigation and the location of its center of gravity (through triangulation). To measure the oscillation period, the student developed a special photodetector consisting of a LED-photoresistor pair, and a perforated tab to alternate between light and shadow areas. All the data processing was performed on an Arduino Uno. As for the load-cell voltages, the signal conditioning and acquisition was performed by three HX711 load-cells amplifiers.

m_0 [kg]	J_0 [kgm^2]	ℓ [m]	d [m]
0.571	0.030	1.5	0.315

Table 1. Trifilar pendulum parameters

ST2: the selected software tools include Autodesk Fusion 360 for the modeling and sizing of all the mechanical components including some 3D-printed parts, the Arduino IDE for firmware development, and MATLAB for data post-processing.

ST3: Figure 1a shows the final trifilar pendulum prototype, with details about the 3D-printed parts, including the photodetector housing and the perforated tab attached to the tray Ⓐ, the load cells holders Ⓑ, the additional support Ⓒ to constrain the tray to rotate around its center, and the tray hooks Ⓓ. As for the tray support, it consists of a pin attached on the tray center, rotating with negligible friction inside a hole created at the top of the support.

ST4: the Arduino code was structured as a state-machine with states related to user-selectable operations that include the load cells calibration, the determination of the tare and net weight, the measurement of the oscillation period, and the estimation of the MoI. The state-machine was implemented on the main loop in the form of a `switch-case` statement. The interaction with user is through terminal. The oscillation period was measured by reprogramming the 16-bit `Timer 1` in input capture mode to track the time elapsed between consecutive rising edges of the photodetector output voltage, as illustrated in Figure 1b. The Interrupt Service Routine (ISR) for the input capture event (TIM1_IC_EV) was implemented for updating the oscillation period every two pulses of the photodetector (otherwise the half-period is measured), and to evaluate a moving average over multiple measurements.

ST5: according to (1), the (theoretical) MoI $J_1^{th} \in \mathbb{R}_{>0}$ of the test object is given by

$$J_1^{th} = k\, mT^2 - J_0 \quad \text{with} \quad k = \frac{g\ell^2}{4\pi^2 d} \tag{2}$$

The constant $k \in \mathbb{R}_{>0}$ is fully defined by the geometrical parameters of the pendulum. During the validation phase, students observed some errors when applying (2) (with nominal value of k) to some test samples (steel disks) with known MoIs. To mitigate the error, a calibration curve was determined by fitting the linear model

$$J_1^{ex} = c_1\, mT^2 + c_2 \tag{3}$$

to the experimental data obtained with the test samples. The results of the calibration tests is shown in Figure 1c. Obviously, the calibration curve must be recalculated whenever the geometric configuration of the pendulum is changed. This refinement ensures that the MoI around the Holybro QAV 250 yaw axis differs by 0.461×10^{-3} kgm^2 from the value derived from its CAD model.

ST6: all the steps of the project were documented by the students in a PDF document, where they justified their design choices from both hardware and software perspectives. They detailed the use of the outlined Arduino code, providing utilization examples. The documentation also contains ideas for future improvements of the device, including the possibility of identifying the MoIs around the roll and pitch axes by employing ad-hoc designed supports.

3.2 Project B

The scope of *Project B* is to develop a device for characterizing the thrust force and torque generated by propellers that actuate small and medium-sized multi-rotors. Such a procedure is useful for accurately modeling the actuation characteristics of the vehicles, especially during the control design process. To fulfill this purpose, three groups of three students each were assigned the twofold task of designing a prototype to measure the desired quantities and implementing a procedure to correlate the recorded wrench measurements with the commanded motor spinning velocity. The rest of the section is devoted to the description of the final version of the testbench, which took inspiration from other prototypes proposed in literature (e.g., in Kulanthipiyan et al. (2023)).

ST0: at the outset, the students gained confidence with the fundamental concepts of multi-rotor dynamics. According to the most widely accepted models, the intensity of the force $f \in \mathbb{R}_{\geq 0}$ and of the torque $\tau \in \mathbb{R}_{\geq 0}$ generated along a propeller spinning axis can be respectively approximated as

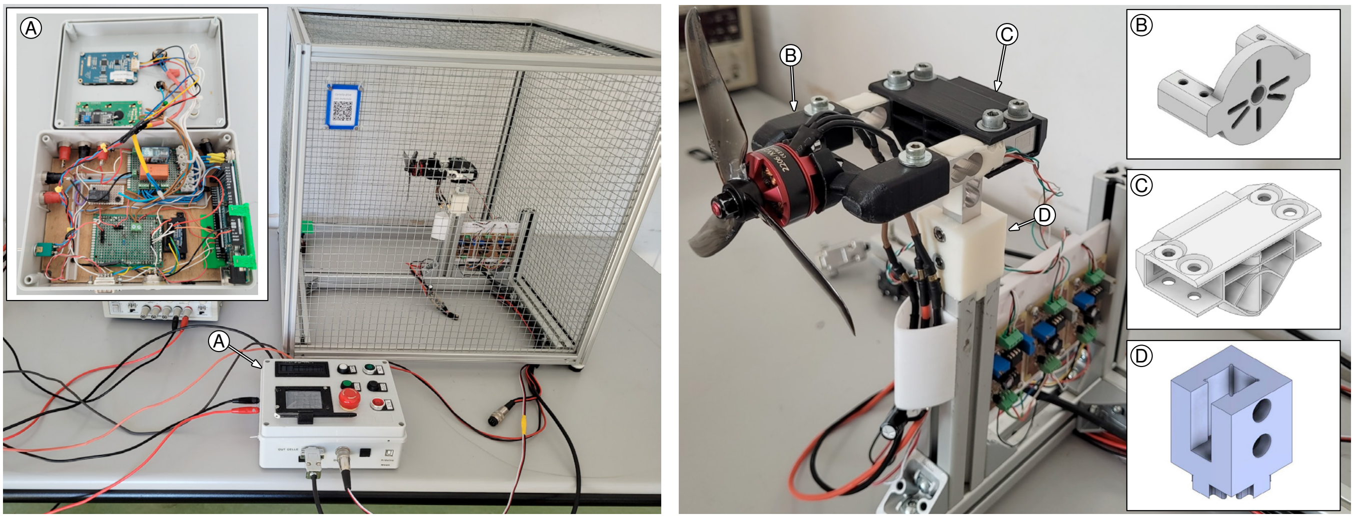
$$f = c_f \omega^2 \quad \text{and} \quad \tau = \kappa c_\tau \omega^2, \tag{4}$$

depending on the square of the assignable brushless motor's spinning rate $\omega \in \mathbb{R}$ through $c_f \in \mathbb{R}_{>0}$ and $c_\tau \in \mathbb{R}_{>0}$. These coefficients, in turn, depend on the aerodynamic and geometric features of the propeller, while the constant κ is equal to $+1$ if the propeller spins in a clockwise direction and -1 otherwise. *Project B* aims to develop a device to determine the coefficients c_f and c_τ for small and medium-sized multi-rotor propellers by correlating accurately measured values of f and τ with the assigned motor input ω using (4). The primary challenge is to achieve precise measurements of force and torque intensity while minimizing the influence of collateral aerodynamic effects. Additionally, it is crucial to implement precautionary measures and design a protective system, as the failure or malfunction of a high-velocity spinning propeller can lead to hazardous situations.

ST1: the outlined testbench comprises two primary mechanical elements: a support for the propeller and a safety cage. Aluminum profiles measuring 40mm×40mm were selected to construct the main framework. The safety cage, consisting of a 53cm cube and crafted from 1.5cm metal mesh, was designed to avoid impeding the rotation of the larger device while ensuring protection for the user. The support was designed so that the motor's spinning axis remains parallel to the ground, with the aim of mitigating the ground effect, i.e., the aerodynamic turbulence induced by the air bouncing on the ground. Additionally, it was tailored for testing two different types of propellers corresponding to two different sizes of multi-rotors. Specifically, the students accounted for a Tarot 6S 380 kV 4008 motor paired with a Tarot 1355 carbon propeller (used in the actuation system of a hexarotor composed of a Tarot 680 pro frame) and a Holybro 2206 2300 kV motor paired with 5-inch plastic propellers (used in the actuation system of the Holybro QAV 250).
Regarding the electronics, the students opted for three 1 kg load cells, an Arduino Mega board, a Nextion display, and a 16-bit ADC device. The load cell signals were processed through a custom PCB equipped with three full-wave rectifiers before being transmitted to the Arduino board, housed in a dedicated electrical panel, through the ADC device. Within the electrical panel, the Nextion display was utilized to present real-time telemetry data from the motor. Furthermore, the microcontroller was responsible for interfacing with the employed Holybro Tekko32 ESC - 35A (the same for both the motors), which converts the signal associated with a desired duty cycle to the corresponding three-phase voltage for the motor, while also providing an estimate of the spinning rate in return. To enhance safety, two microswitches and associated protection circuitry were installed on the lower edge of the safety cage, ensuring the interruption of current to the motor in the event of cage lifting.

ST2: from a software perspective, the students selected Arduino IDE for programming the microcontroller, which handles communications with sensors and the ESC. This latter was programmed using BLHeliSuite32. Measurements processing and motor commands sending were delegated to an externally connected computer running MATLAB&Simulink, enabling a higher level of automation in executing multiple consecutive tests and enhancing the accuracy of parameter estimation. For the design of 3D-printed components, AutoCAD, Autodesk Inventor, and Solidworks were utilized, while KiCAD and EasyEDA were employed for PCB design.

ST3: Figure 2a shows the overall setup. The electrical panel Ⓐ, housing the ADC, Arduino Mega board, and Nextion display, is positioned outside the cage and acts as an interface between the sensors, ESC, external computer,



(a) (b)

Fig. 2. *Project B*: (a) final prototype of motor testbench including the safety cage and the electrical panel; (b) details of the motor support and measurement system.

and power supply. Figure 2b focuses on the propeller support and the measurement system composed of three load cells. Two are placed tangentially and perpendicular to the disk supporting the motor Ⓑ, allowing the torque generated by the propeller to be inferred by recording a pair of opposite forces from a fixed distance from the motor axis. These load cells are connected through the support Ⓒ to the third, vertically center-aligned load cell, which directly measures the force produced along the motor axis and is fixed to the main structure via Ⓓ. All the supports are custom-designed to minimally interfere with the airflow produced by the propeller from an aerodynamic point of view.

ST4: the students designed the Arduino code to manage communication with the ESC, load cells, and Nextion display. They also implemented MATLAB & Simulink procedures to calibrate the load cells before any experimental campaign and to autonomously collect force and torque measurements at different motor spinning rates, indirectly defined by a desired duty cycle. The collected data from multiple experiments were then processed to estimate the coefficients c_f and c_τ by fitting the experimental data to the model (4) using a least-square approach.

ST5: the students conducted numerous tests to validate the testbench, achieving consistent results after proper calibration of the measuring system. The estimated values of c_f and c_τ for both the Tarot and Holybro propellers are consistent with the information provided in the datasheets.

ST6: the students summarized their working procedures in a PDF document, detailing the steps taken throughout the project's development and explaining how they addressed encountered issues. Additionally, they formally outlined the test procedure through written and video guides and provided a comprehensive description of the statistics gathered during the experiments, including the estimated values of c_f and c_τ for the two tested propellers. They also proposed ideas for future improvements towards the further engineering of the testbench.

4. DISCUSSION ON EDUCATIONAL IMPLICATIONS

To assess the educational implications of the proposed B.M.E. thesis projects, we collected feedback on their effectiveness from the students. In doing this, we administered a questionnaire which also required some specific aspects to be evaluated numerically (on a scale from 1 to 10).

First, we recorded that facing the final exam with a group project offers numerous advantages over an individual thesis. Most students admitted that this modality affords them to engage in practical aspects as compared to the more traditional individual thesis, which often focuses on theoretical analysis or state-of-the-art revision. Along the same lines, they appreciated the positive aspects of workload distribution, the possibility of relying on teammates for support in difficult situations, and the beneficial exchange of diverse ideas. All the students recognized that this experience allowed them to improve their ability to work effectively in a team, representing a crucial skill in the professional world. Nevertheless, they also highlighted some drawbacks, such as the fact that the outcomes and progress of the project depend only partially on individual efforts, along with the need to adapt to shared decisions and the potential need to mitigate conflicts. In this sense, the regular update meetings with the tutors are also intended to prevent negative situations from becoming excessive.

Furthermore, for the successful accomplishment of the project, the students agreed on the usefulness of the theoretical notions related to basic disciplines, such as math and physics (rated 7.44/10), as well as those learned in mechanical-oriented courses (rated 7/10). They recognized the greater utility of the concepts taught in electronic courses (rated 8.11/10), and above all in computer and control courses (rated 9/10). On the other hand, they acknowledged that the proposed thesis projects primarily help them acquire new practical skills, such as designing and developing 3D-printed components and coding and implementing a C++ program. Furthermore, the students also experienced an improvement in several soft skills, especially the ability to handle unexpected events and the autonomy in planning the achievement of an objective given some hard time constraints.

Moreover, students reported that such multi-disciplinary activity allows them to give concreteness and clarity to what they have learned in class by translating many theoretical concepts into practical actions (opportunity rated 7.11/10), thus deeply understanding the interconnections between the various disciplines of mechatronics (opportunity rated 8.56/10).

In conclusion, the students expressed satisfaction with the work done and the methods proposed (rated 8.22/10), considering the project to be moderately challenging (rated 6.67/10). Furthermore, they all agreed on the educational value at the end of their mechatronics engineering studies, as well as personal growth to face future challenges in the professional world.

5. CONCLUSIVE REMARKS

The integration of group projects for B.M.E. final exam offers numerous educational advantages, as demonstrated by the multi-rotor testbench design projects reported in this paper. These thesis projects significantly improve interpersonal and teamwork coordination skills, essential for success in the professional career. By fostering multidisciplinary learning, students are able to draw on knowledge from mechanics, electronics, computer engineering, and automatic control, thereby gaining a comprehensive understanding of mechatronics engineering.

The learn-by-doing approach involved in these projects strengthens the theoretical knowledge acquired in both fundamental disciplines and specialized courses. Additionally, students acquire new practical skills, such as using advanced software tools for 3D modeling and circuit simulation, or the mechanical prototyping with 3D printing technologies. Moreover, they have the opportunity to improve other essential professional skills like teamwork, communication, and project management through collaborative work. Encountering real-world issues and constraints also develops their creative problem-solving abilities.

Overall, group projects for final exam prepare students for real-world engineering challenges by combining theoretical knowledge with practical application, fostering a collaborative learning environment, and equipping them with diverse technical skills. The balanced integration of technical disciplines with professional skill development provides an ideal bridge between classroom learning and career readiness. This holistic educational approach ensures that graduates are well-prepared to excel in their future careers.

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