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Development of a Modular and Low-Cost Educational Prototype for Teaching Control Engineering

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Abstract: This article presents the design and implementation of a low-cost, modular training platform designed to conduct control engineering exercises that complement knowledge of modeling, identification, and control of dynamic systems. It is based on experiments with three plants with different open-loop responses: overdamped, underdamped, and unstable. An analog proportional-Integral-Derivative (PID) controller is designed for each, and its digital conversion is implemented using an Arduino Uno platform. This allows the control system's performance to be determined by measuring overshoot and response time.

Key words: Educational prototype, linear control, plants with operational amplifiers, PID control.

1. Introduction

Control engineering is a branch of engineering that focuses on the analysis, modeling, design, and implementation of systems capable of controlling the behavior of dynamic processes so that they operate in a stable, precise, and efficient manner, using techniques from different disciplines such as mathematics, physics, electronics, computer science, and instrumentation. Its impact on industry, technology, and everyday life makes it a strategic discipline for scientific and economic progress.

With the arrival of the fourth industrial revolution, the integration of advanced digital technologies into industrial processes has gained great relevance, enabling the creation of smart factories [1, 2]. In this scenario, embedded systems have become indispensable, replacing traditional analog systems [3], offering advantages such as greater energy efficiency, robustness, reliability, and real-time data processing capacity, making them ideal for operating under adverse conditions and continuously [4]. Consequently, this change has consolidated the importance of Control Engineering within Industry 4.0, motivating higher education institutions to design educational programs that address the study and implementation of these systems.

However, teaching these areas faces significant challenges, especially due to the lack of specialized laboratories and equipment [5]. A clear example of this situation is observed at the University of Veracruz, where EEs (Educational Experiences) such as Linear Control and Digital Control are mostly taught theoretically.

While mastery of mathematical fundamentals is essential, teaching control systems should not be excessively theoretical or disconnected from practical applications [6]. The lack of specialized equipment prevents students from putting the concepts studied in class into practice, forcing them to invest time in building systems, when the main focus should be on experimentation.

This is where the need is to develop innovative solutions that allow students to focus on practice, without being limited by the availability or construction

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of the hardware. One solution to this problem is presented in Foulis and Papadopoulou [7], where the Department of Automation Engineering at Alexander Technological Educational Institute of Thessaloniki (ATEI), Greece, designed an inexpensive lab kit, equipped with an Arduino board and compatible sensors, to meet the need for hands-on practice in higher and graduate education. This kit allows students to perform basic hands-on practice, such as light-emitting diode (LED) brightness control and temperature control.

Another example is found in Werth, Faller, Liechtenecker and Ungermanns [8], where an Arduino-based RCP (rapid control prototyping) designed for position control of a DC motor is presented. It should be noted that RCP is a methodology that allows the use of reprogrammable tools to evaluate the performance of controllers before their final implementation. With the use of this methodology, a significant improvement in student evaluation was observed, proving its usefulness as a teaching tool.

Following this approach, teaching prototypes become a tool that allows key concepts to be taught in a tangible way. Therefore, this research aims to design and implement an innovative educational prototype for teaching and learning control systems. To this end, the use of analog tools in combination with digital systems is considered, providing a comprehensive and practical experience.

This proposal emerges as an alternative that seeks to compensate for the lack of specialized laboratories in the field, allowing students to interact with different proportional-Integral-Derivative (PID) controllers, analyze the behavior of different systems (stable, unstable, and of different orders), and compare the performance of analog control systems with their digital counterparts.

2. Objective

The overall objective of this project is to design an interactive, affordable, and portable educational prototype for use as an educational support tool in teaching analog and digital control systems. This prototype combines PID controllers and three systems or plants with typical response dynamics, combining the use of analog electronics and embedded systems, allowing for educational autonomy in experimenting with control systems.

3. Description of the Prototype

The proposed prototype consists of three PCBs (printed circuit boards). The first integrates three plants with different open-loop step responses (underdamped, overdamped, and unstable) and built with operational amplifiers. These were chosen to be useful in the development of an introductory Linear Control course. The second will include the PID controller built using operational amplifiers, whose P, I, and D gains can be adjusted using variable resistors, allowing students to tune and modify the behavior of the plants according to parameters defined by the teacher. Additionally, and as a third board, a development system based on Arduino Uno and some circuits for digital signal processing are built. Through this board, a digital version of the PID controller can be implemented. The student can enter the controller gains and select an appropriate sampling period, facilitating a comparison between analog and digital strategies.

3.1 PCB for Analog Plants

This printed circuit board consists of three analog plants with the following characteristics.

For the plant with overdamped response the following mathematical model was considered:

$$\frac{V_o(s)}{V_i(s)} = \frac{1000}{s^3 + 50s^2 + 600s + 1000} = \frac{1000}{(s + 32.46)(s + 1.98)(s + 15.55)} \quad (1)$$

As can be seen, the transfer function presents three different real poles. This characteristic allows the system to be implemented with three operational amplifiers in cascade, and the following transfer function, which corresponds to that of a first-order system, is used to represent each pole.

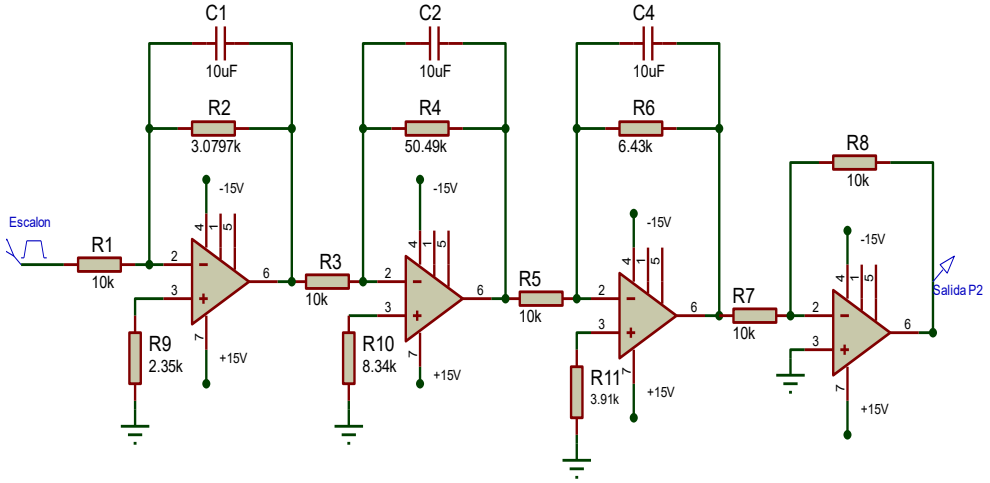

Fig. 1 Circuit for the overdamped plant.

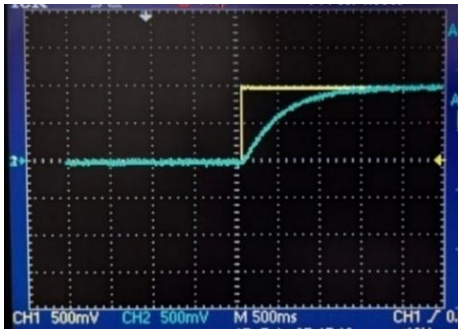

Fig. 2 Experimental response of the overdamped plant.

$$G_1(s) = -\frac{R_2}{R_1}\left(\frac{1}{R_2Cs+1}\right) \tag{2}$$

It's important to note that, due to the structure used, the implementation featured a phase inversion. For this reason, a fourth inverter stage was added to maintain consistency with the proposed mathematical model. The circuit is as follows:

Finally, the system was simulated. Fig. 1 shows the model, and its open-loop experimental step response is presented in Fig. 2.

For the plant with underdamped response, the structure of a Sallen-Key filter was used, described by the following circuit.

Whose transfer function is given by:

$$\frac{V_o(s)}{V_i(s)} = \left(1+\frac{R_b}{R_a}\right)\frac{\frac{1}{R^2C_1C_2}}{s^2+\frac{1}{R}\left(\frac{2}{C_1}-\frac{R_b}{R_aC_2}\right)s+\frac{1}{R^2C_1C_2}} \tag{3}$$

By selecting the values of the resistors and capacitors, the following model was obtained:

$$\frac{V_o(s)}{V_i(s)} = \frac{1.3201}{s^2+0.6s+1} \tag{4}$$

Finally, the circuit simulation was performed, obtaining the following step response:

For the plant with unstable response the following circuit was used:

Whose transfer function is given by:

$$\frac{V_o(s)}{V_i(s)} = \frac{\frac{R_3}{R_1R_2C_1}}{s-\frac{R_3}{R_2R_4C_1}} \tag{5}$$

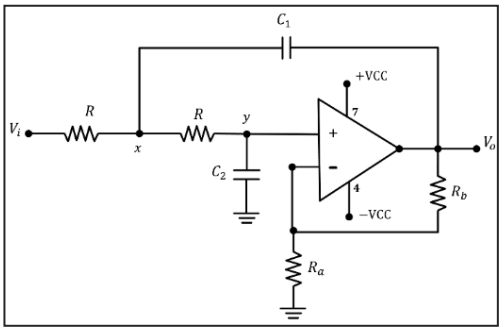

Fig. 3 Second-order system with operational amplifier.

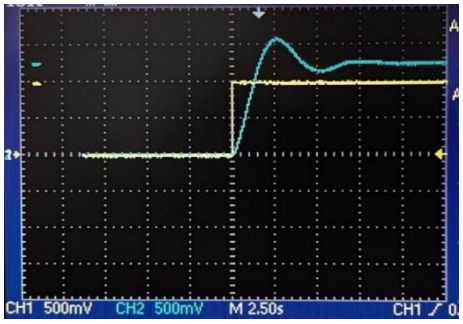

Fig. 4 Experimental response of the underdamped plant.

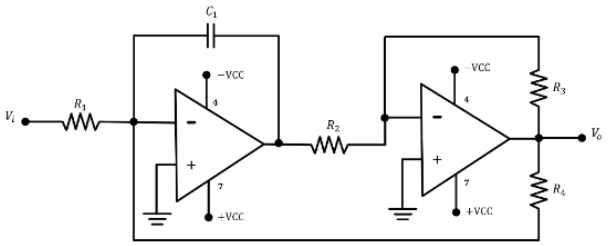

Fig. 5 Unstable first-order system.

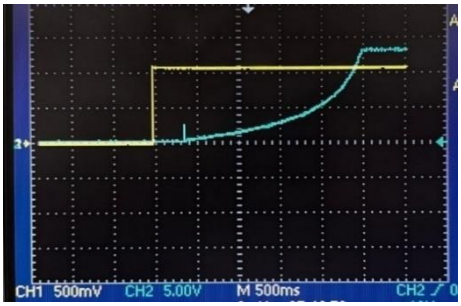

Fig. 6 Experimental response of the unstable plant.

And you can see that it has an unstable pole. Fig. 6 shows the step response, obtained experimentally.

The printed circuit board integrates the three analog plants implemented with 741 uA operational amplifiers and resistors and capacitors with standard tolerances.

The PCB integrates:

1. Variable resistors on each plant, allowing adjustment of the pole placement or the system time constant and, consequently, the step response.

2. TPs (test points) labeled: PLANT 1 OUTPUT, PLANT 2 OUTPUT, and PLANT 3 OUTPUT, for measuring open-loop responses with an oscilloscope, as well as the output of the digital controller.

3. Pins for connecting a function generator to the input of the three systems or the output of the analog controller (Board 2).

4. A pin dedicated to the output of the analog PID controller (only when Boards 1 and 2 are connected).

5. Jumpers for selecting the plant to be controlled.

6. Pins to connect the inputs and outputs of the three systems to the Arduino Uno pins.

7. A pin dedicated to closing the control loop (between Boards 1 and 2).

8. Clear silkscreen printing allows for identifying the input, output, ground (GND), and each analog output pin.

The following figure shows the constructed PCB:

3.2 PCB for the Analog PID Controller

The circuit used for the analog PID controller consists of six operational amplifiers, arranged as shown in Fig. 8. It shows the construction of a comparator, a multiplier, an integrator, a derivative, an adder, and an amplifier for inserting a disturbance signal.

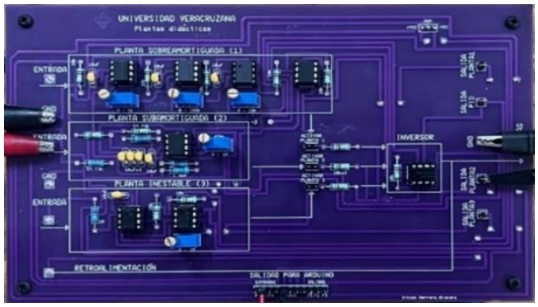

Fig. 7 PCB 1: Analog plants.

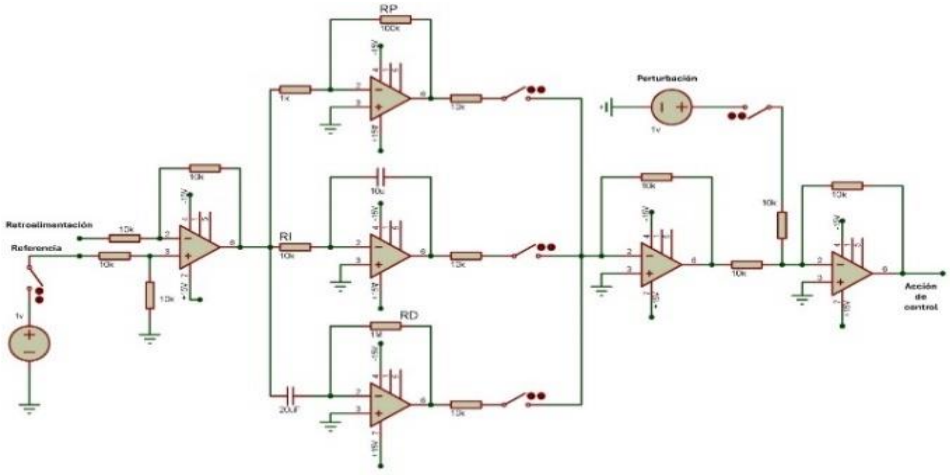

Fig. 8 Analog PID controller circuit.

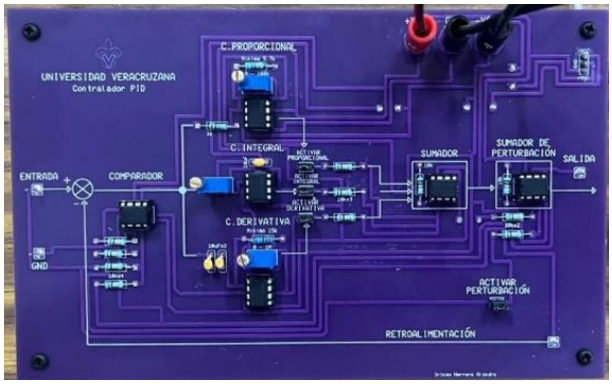

Fig. 9 PCB 2: Analog PID controller.

Fig. 10 PCB 3: Digital PID controller.

The PCB contains a single analog PID controller; by adjusting the resistive values of each control action, it is possible to control any of the three analog plants designed.

The PCB integrates:

1. Pins for connecting a function generator to the controller input.

2. Variable resistors for each PID action, which allow checking the results obtained during the tuning processes.

3. Jumpers to enable or disable each control action (Proportional, Integral, or Derivative).

4. A jumper to inject a 1V step disturbance.

5. A pin for the PID controller output (only when Board 1 and Board 2 are connected).

6. A pin to close the control loop (between Board 1 and Board 2).

7. ±15 V power supply.

8. Clear silkscreen to identify input, output, and GND pins, as well as each part of the PID controller.

The following figure shows the constructed PCB:

3.3 PCB for the Digital PID Controller

An Arduino Uno development system is mounted on this board, and some operational amplifier circuits are added to facilitate digital signal processing. Fig. 10 shows the built board.

4. Experiments and Results

Each of the plants was tested experimentally, and the results were compared with the responses obtained by simulating their mathematical models using Matlab/ Simulink.

4.1 PID Controller—Overdamped Plant

The PID controller was designed using the reaction curve method proposed by Zieglers and Nichols. Figs. 11 and 12 show the simulation diagram and the responses obtained using Simulink:

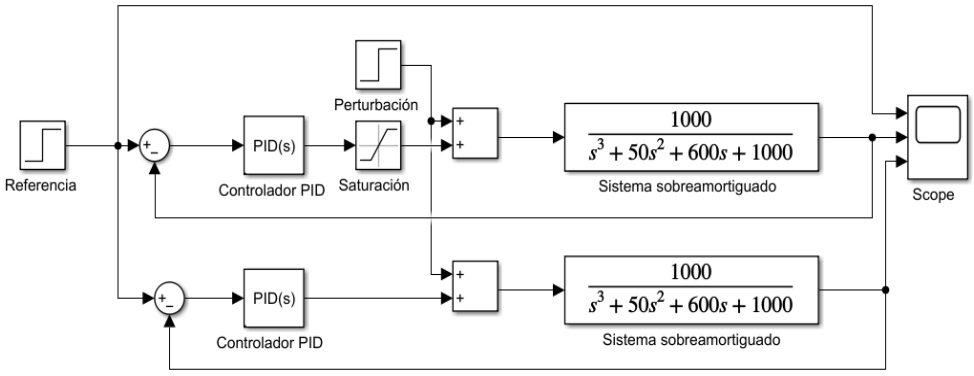

Fig. 11 Simulation diagram for the overdamped plant.

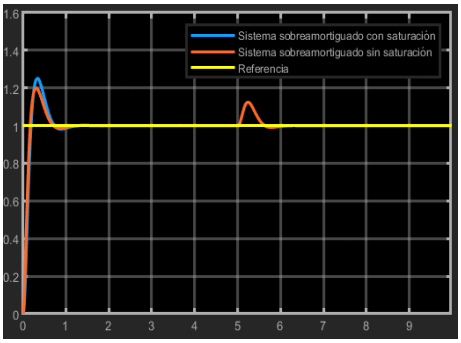

Fig. 12 Simulated response for the overdamped plant.

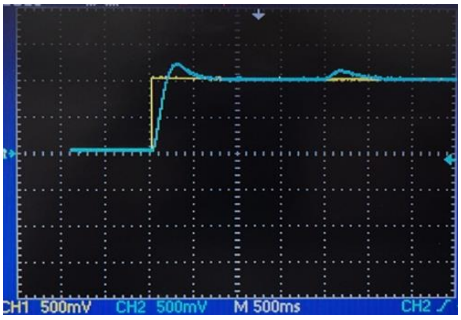

Fig. 13 Experimental response with analog PID controller for the overdamped plant.

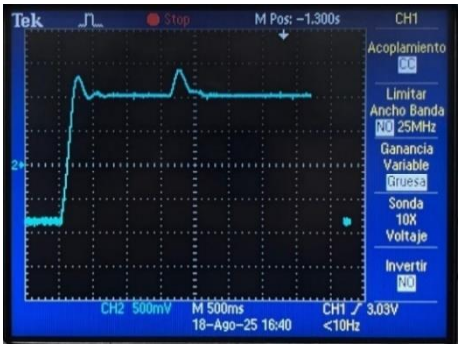

Fig. 14 Experimental response with digital PID controller for the overdamped plant.

It can be seen that the orange curve corresponds to the unsaturated response. This response, obtained under ideal conditions, exhibited stable and rapid dynamics, with a single overshoot of approximately 20% and evident disturbance rejection, confirming what the Ziegler-Nichols rules provide a good starting point for future fine-tuning. The blue curve considers saturation of ±12 V; therefore, it presented a higher %OS, highlighting the limitations imposed using LM741 operational amplifiers.

Finally, Fig. 13 shows the control loop response of the real physical system implemented with operational amplifiers and observed using an oscilloscope. It can be seen that the response is similar to the dynamics of the blue curve shown in Fig. 12, confirming that the design objectives and, therefore, the educational purpose of the experiment were met.

4.2 PID Controller—Underdamped Plant

In this case, the PID controller design was based on locating the closed-loop poles in a location that satisfied a maximum overshoot of 20% and a response time of two seconds.

Applying the same logic to the underdamped plant, the simulation results are shown in Figs. 15 and 16, and the experimental results in Figs. 17 and 18.

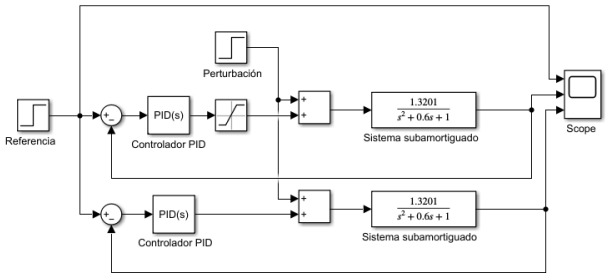

Fig. 15 Simulation diagram for the underdamped plant.

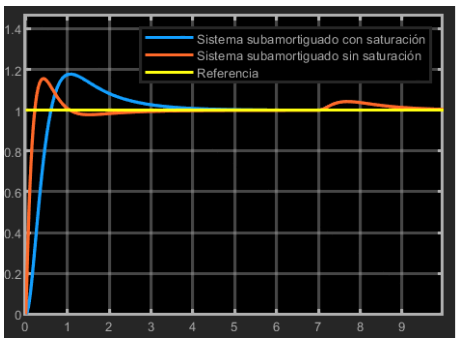

Fig. 16 Simulated response for the underdamped plant.

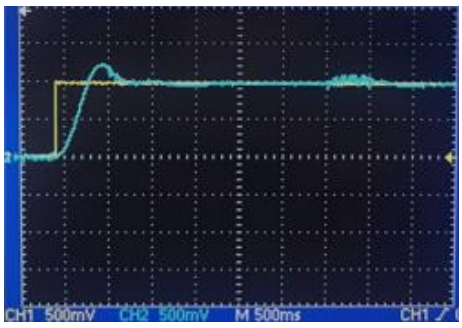

Fig. 17 Experimental response with analog PID controller for the underdamped plant.

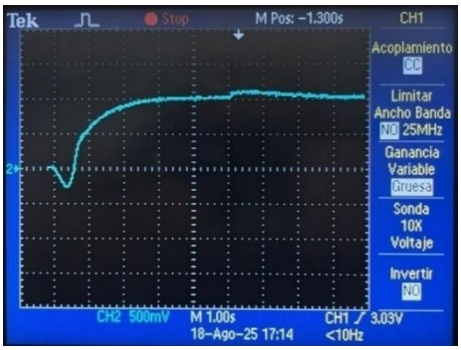

Fig. 18 Experimental response with digital PID controller for the underdamped plant.

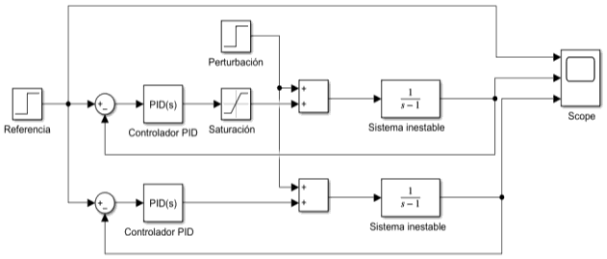

Fig. 19 Simulation diagram for the unstable plant.

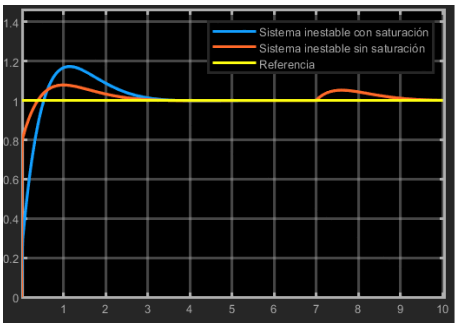

Fig. 20 Simulated response for the unstable plant.

Fig. 21 Experimental response with analog PID controller for the unstable plant.

4.3 PID Controller—Unstable Plant

By constructing the root locus graph of the system, the location of the PID controller zeros and their respective gains were determined.

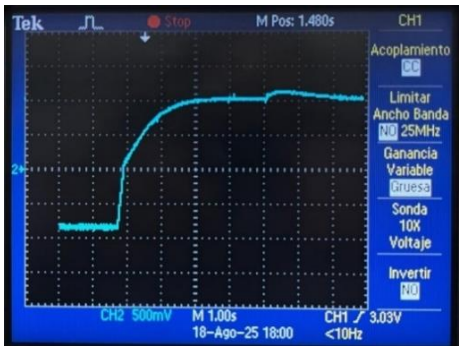

Fig. 22 Experimental response with digital PID controller for the unstable plant.

Applying the same logic to the unstable plant, the simulation results are shown in Figs. 19 and 20, and the experimental results are shown in Figs. 21 and 22.

5. Conclusions

This project describes the design and construction of a low-cost, modular, and educational prototype for laboratory practicals in both analog and digital linear control engineering. It is based on the development of three plants built from operational amplifiers and with open-loop responses of the overdamped, underdamped, and unstable types. The system was tested with twenty students in a formal undergraduate course in linear control, and favorable data were obtained regarding its use and contribution of practical knowledge to the teaching of control engineering. The theoretical designs were experimentally validated for both plant modeling and PID controller design. The control systems were tested in servo and regulator modes, and their good performance was assessed. The most challenging aspect was the implementation of the digital controllers on the Arduino platform, due to the presence of latencies and interconnection difficulties, which are evident in the response graphs. The design and procedures can be easily shared with students, and they can be encouraged to build them as part of their training. Future work plans include implementing advanced control techniques.

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