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iJOE International Journal of Online and Biomedical Engineering

iJOE | eISSN: 2626-8493 | Vol. 21 No. 12 (2025) | OPEN ACCESS

https://doi.org/10.3991/ijoe.v21i12.57673

PAPER

Project-Based Learning to Enhance the Teaching of Control Systems: Integrating Embedded Systems and Signal Processing

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ABSTRACT

This paper presents a project-based learning approach designed to enhance the teaching of control systems. The project incorporates key foundational concepts, including embedded systems programming, filter design, and control system theory, to control the speed of a direct current (DC) motor. Through hands-on activities, students gain practical experience in applying classroom theories and concepts to real-world situations. The project is suitable for courses focusing on control theory or embedded systems and was introduced as part of a senior-level introductory control systems course. Student feedback indicated that the project's practical nature significantly improved their understanding and reinforced theoretical knowledge. This paper describes the project and the project's scope and provides an overview of student feedback.

KEYWORDS

control systems, speed control, microcontroller, project-based learning, and proportional integral derivative controller

1 INTRODUCTION

Control systems play a significant role in a wide range of applications, including robotics, industrial processes, manufacturing, and environmental regulations. These systems are essential for ensuring precision, efficiency, and automation in various industries, enabling machines and processes to operate with minimal human intervention. As control systems become more sophisticated and interconnected, the demand for skilled engineers continues to grow. Professionals with expertise in control theory, embedded systems, and signal processing are needed to design, optimize, and maintain these complex systems. Advancements in artificial intelligence, the Internet of Things (IoT), and smart automation further emphasize the

Alqudah, Y. A., Sababha, B. H. (2025). Project-Based Learning to Enhance the Teaching of Control Systems: Integrating Embedded Systems and Signal Processing. *International Journal of Online and Biomedical Engineering (iJOE)*, 21(12), pp. 4–20. https://doi.org/10.3991/ijoe.v21i12.57673

Article submitted 2025-06-15. Revision uploaded 2025-08-12. Final acceptance 2025-08-12.

importance of developing strong engineering skills to meet the evolving challenges in this field [1], [2].

Effective teaching and learning pedagogies require the use of various available techniques and resources to help students attain the intended learning outcomes. Other than the conventional "talk and chalk" passive learning approaches, effective educators use different active learning techniques that are student-centered [3]. Active learning techniques include interactive questions and answers, collaborative thinking and sharing, debates, group discussions, and demonstrations using tools to better present ideas, like using visuals and tangible models [4]. In addition, active learning includes more complex approaches like project-based learning, problem-based learning [4], game-based learning [5], competition-based learning [6], and flipped teaching [7], among others.

When traditional instructional methods fall short in preparing students to meet challenges in the real world, an approach to learning is utilized through building projects, *i.e.*, project-based learning (PBL) [8]. PBL is a student-centered approach that emphasizes hands-on learning and practical learning experiences [9]. PBL enables students to develop a deeper understanding of theories and engineering concepts while improving their problem-solving, creativity, communication, and critical thinking skills [10]–[12]. Using projects that simulate real-world problems allows students to apply their knowledge to solve practical problems. This, in turn, enhances the readiness of engineering graduates to fulfill industry demands [13], [14].

PBL has many benefits in improving knowledge acquisition and providing engineering students with important industry and business skills. However, despite its advantages, the implementation of PBL can be quite challenging. There are several obstacles that need to be addressed to successfully implement PBL in engineering education. These challenges may include issues related to curriculum design, student engagement, assessment methods, and instructor training and support [13]. Hence, researchers and educators need to continue to implement, evaluate, and improve PBL implementation.

In control systems projects, students design and build systems that are controlled through a computing system, namely a microcontroller unit (MCU). The microcontroller would interact with the environment through input sensory units and output actuators. The software would understand the environment by sampling input signals and then processing them before issuing commands to control the output actuators.

Project-based learning in control systems enables students to connect and integrate various skills across multiple fields, such as digital signal processing, embedded hardware and software design, and control systems. This hands-on approach encourages practical problem-solving and fosters a deeper understanding of theoretical concepts by applying them to real-world scenarios. Furthermore, it necessitates a thorough understanding of hardware components and electrical circuits, as students must design, implement, and troubleshoot systems effectively [2]. By engaging in such projects, students enhance their technical expertise, critical thinking abilities, and teamwork skills, preparing them for future challenges in engineering and technology.

Based on the successful adoption of PBL in embedded systems [15], signal processing [16], [17], and wireless communication [18], this paper presents a PBL approach that integrates fundamental concepts from various topics into a single project. The project would comprise embedded software development, filter design to filter noisy sensory signals, and control systems to develop a proportional integral derivative (PID) controller. The project is a major component of a senior control systems class.

This PBL approach offers many benefits. It provides students with a deeper understanding of the theory and allows them to apply it to a practical system. It fosters both problem-solving and project-management skills as students troubleshoot issues encountered during the project and budget their time and resources to complete it. Finally, it bridges the gap between academia and industry as students engage in solving practical problems. This approach provides students with skills and competencies to solve problems in a real-life context.

The educational designs for collaborative engineering design activities and their impact on students' collaboration are reviewed by Helden *et al.* [19]. The review emphasizes the importance of collaborative learning in engineering education and the need for a deeper understanding of how elements in an activity affect collaborative learning. The insights can help practitioners make evidence-informed decisions when creating collaborative engineering design courses. The paper concludes that collaborative learning in engineering design led to the achievement of learning objectives. It also provides valuable insights for educators and researchers in this field.

Rodriguez-Sanchez *et al.* [20] categorize collaborative learning in engineering education into three learning models: classroom-based, laboratory-based, and project-based. The classroom-based model involves an instructor delivering lectures using a collaborative software environment, where students can comment on the material and enrich it during the lectures. The laboratory-based model involves small and homogeneous teams of students collaboratively performing a list of experiments using appropriate software tools. The PBL model involves small teams of students solving engineering problems using an assortment of collaborative software tools. The teams are generally allowed to define their own problem statement within the scope of the course.

The work presented in [20] concentrated on the PBL model and shows its effectiveness in international collaborative projects using open-source tools in teaching and learning digital electronic systems. The study confirms that such projects can enhance students' problem-solving skills, teamwork, and cross-cultural communication. Additionally, the paper provides insights into the challenges and opportunities of working in diverse and multi-site teams.

PBL is useful for teaching advanced and multidisciplinary courses [20]. Control systems, signal processing, and embedded systems are essential for advanced and multidisciplinary courses in engineering education. PBL is an appropriate approach to help students better attain technical knowledge, in addition to other important non-technical skills. The following are important case studies from the literature addressing the mentioned or similar courses.

Najeeb and Memon [21] present an experience of developing a PBL approach for an undergraduate control systems laboratory course during the COVID-19 pandemic. The purpose is to utilize available free online resources when having no access to resources in the lab or licensed software such as MATLAB. The authors utilize an online tool called tinkercad to have students practice fundamental control systems concepts during the design and simulation of analog and digital control closed-loop systems [21].

Perales *et al.* [22] propose a problem-based approach in the control systems domain [22]. The researchers request students to design and implement a temperature control system through the utilization of basic components except for a microcontroller that can be programmed using the C programming language. The project concentrates on many fundamental and conceptual components in low-level circuits and electronics. The objective is to design a temperature sensor and two actuators to switch on and off the cooling and heating appliances and implement an appropriate control strategy [22].

Kataria *et al*. [23] use the PBL approach in a first-year 6-credit hour course. The course is a fundamentals of engineering course with four studio hours and two direct contact hours per week [23]. The course material is delivered using a hybrid method, where lecturers directly deliver some of the content while other content is supposed to be attained through self-directed learning. The course contains several 3-week units in basic electric circuits, digital logic, mechanics, and dynamics, as well as embedded systems and controls. The students were required to design and build a low-cost material handling machine. The project requires basic control functionalities. Students need to utilize what they learned in electric circuits to build the power supply. In addition, mechanical parts and a direct current (DC) motor are utilized to move a conveyor through gears. The students had to build a counter through basic logic circuits and a data acquisition system through sensors read by a microcontroller unit. The project was used to help learn and understand various knowledge concepts, competencies, and skills in various fields in electrical engineering, embedded systems, and control, in addition to teamwork and other important skills. The course was delivered by a team of multidisciplinary engineers to cover all units in the different knowledge areas [23].

Fernández-Samacá *et al*. [24] offer their experience in the development of the curriculum and delivery plan of four control systems courses using a PBL approach. The approach is applied in two three-credit hour courses and two one-credit hour lab courses. The project assigns teams of students based on a real control problem in the industry. The authors present how the PBL approach is implemented, starting from the problem definition through the implementation plan that includes team formation, support, and assessment. The work concludes that the assessment tools help the students better attain the required learning outcomes. The authors measure these results through peer and self-assessments [24].

Sanfilippo and Austreng [25] present their contribution to enhancing teaching embedded systems through PBL in [25]. The authors organized their approach into three parallel layers: the theoretical layer, the laboratory layer, and the application layer. The theoretical layer is to deliver the needed theoretical knowledge, while the laboratory layer is to train and educate students about the hardware devices and tools they will be using to implement their projects. Finally, in the application layer, students combine what was learned in the previous two layers to implement their lab group projects [25].

This paper is organized as follows: Section 2 presents the method of the proposed project. Section 3 covers implementation and experimentation work. The results of the implementation and student feedback are presented in Section 4, and finally, Section 5 concludes the paper.

2 PROPOSED PROJECT

Motor speed control is an important component in various industrial applications, including manufacturing and automation, heating and ventilation, material processing, and transportation. It allows for the precise regulation of machinery and equipment, ensuring optimal performance and operational safety. By adjusting the speed of motors to match specific requirements, industries can enhance productivity, reduce wear and tear on components, and minimize energy consumption. Effective speed control also contributes to improved process accuracy, reduced mechanical stress, and extended equipment lifespan, making it a critical aspect of modern industrial systems.

In this project, motor speed control will be used to model, analyze, and design a controller. The project put the theories and concepts learned in the Control class into practice through a hands-on application. The specific learning outcomes of the projects are listed below:

- Model a DC motor and experimentally obtain its parameters.
- Analyze the system to determine its open-loop behavior.
- Design and implement a PID controller to control the speed of the motor to meet performance criteria.
- Compare experimental and theoretical system response.

For this project, a low-cost gear motor with a quadrature encoder to measure the speed is used. A motor driver (MD) to provide sufficient power to the motor and to control its direction is needed. A pulse-width-modulated (PWM) signal generated by the microcontroller is used to change the speed of the motor. These components are summarized in Table 1. Figure 1 shows the project components. We describe the main components of the project.

Table 1. Part specification

Part	Description
Microcontroller	Arduino universal networked object (UNO) board based on the ATmega328P microcontroller
Motor driver	L298N Motor Drive Controller Board Module Dual H Bridge DC Stepper for Arduino
Motor	12V DC High Speed 300 RPM Gear Motor with Encoder for Arduino
Arduino integrated development environment (IDE)	1.8.15 or higher

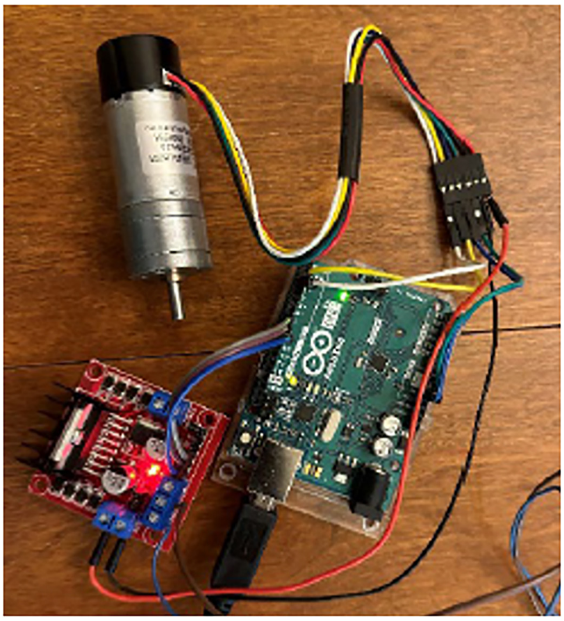

Fig. 1. Project components showing motor, motor driver, and Arduino unit

2.1 Block diagram

The system is composed of a microcontroller and a motor, as shown in Figure 2. The microcontroller generates a signal that is fed to the motor through the motor driver. The motor has an encoder to estimate the speed, and the encoder signal is read by the microcontroller.

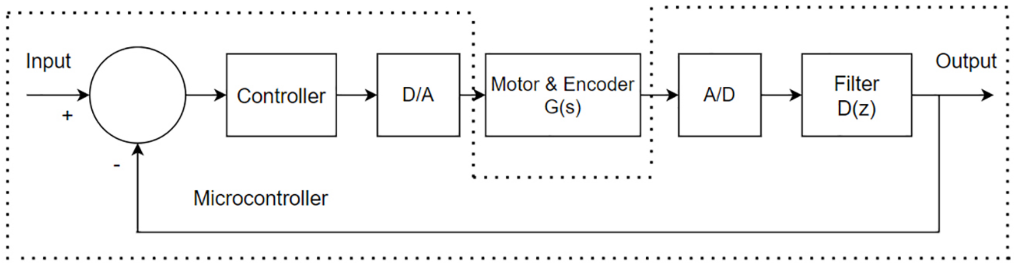

Fig. 2. System block diagram

2.2 Programming

The programming of the microcontroller requires a background in programming, as it involves writing and debugging code to control hardware components. Most students are already familiar with Arduino programming, either because they have studied it in a dedicated course or have gained experience through other coursework. This prior knowledge provides a strong foundation for working with microcontrollers, allowing students to better understand coding structures, interfacing with sensors and actuators, and troubleshooting potential issues. As a result, they can more effectively apply their skills to real-world applications and further develop their expertise in embedded systems programming.

In this project, the microcontroller is programmed to generate the set speed, calculate the actual speed of the motor based on the feedback signal from the encoder, compute the error between the required and feedback speeds, and generate the PWM signal based on the speed controller. To achieve these tasks, typically, interrupts are used to read the motor encoder signal. The program uses the signal to calculate the motor speed. Students can search for many posted examples online to help them start programming, or a skeleton script can be provided.

2.3 Filtering

The motor encoder uses generated pulses as the motor rotates to measure speed by counting the number of pulses in each time. As a result, the calculated motor speed appears noisy and fluctuates between values. A low-pass filter is needed to smooth the signal. Since the signal is calculated by the microcontroller, a digital filter is implemented to smooth the signal and remove any fluctuations.

2.4 Design and implement the speed controller

Before being able to design and implement the controller, the system needs to be modeled. The open-loop system can be represented as shown in Figure 3. The first block represents the transfer function between the motor speed and the applied signal (V). In this work, the transfer function is approximated by a first-order system. The second block represents the digital filter. The relationship between filtered motor speed and applied voltage is represented by a second-order equivalent of both transfer functions. Controllers are designed based on the system model obtained above and are implemented by approximating the integration and derivation components.

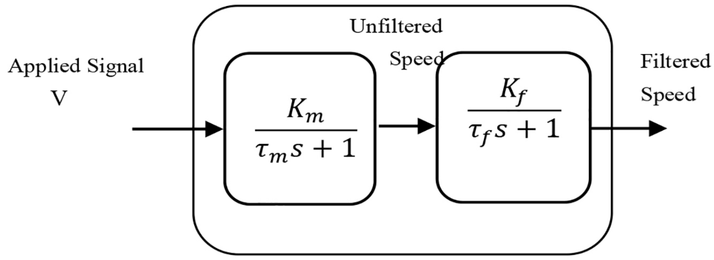

Fig. 3. Open-loop model

Note: The model shows the filtered and unfiltered speed as outputs and applied voltage as input.

3 IMPLEMENTATION AND EXPERIMENTATION

The project can be assigned to any senior-level course that introduces control systems, signal processing, or embedded systems. It assumes theoretical development is covered in the classroom lectures. The project reinforces learning using a practical application.

Students are loaned hardware components that include a motor, motor driver, and a microcontroller. They are allowed lab access so they can use power supplies and measurement tools. The project can be offered as a guided assignment with directions to complete sequential tasks or as an unguided assignment. The assigned tasks in the project are highlighted below.

a. Task 1: Hardware and software setup

Students are asked to connect the motor, driver, and microcontroller and test their setup by applying a signal to run the motor. Schematics, as well as software, can be provided. Students can write their own script or run a provided script to ensure their setup is correct. A typical microcontroller will use an analog write function to generate an analog signal that can be applied to the motor driver. By observing and capturing the motor response, students can build confidence that their setup is correct and can proceed to the next tasks.

b. Task 2: System modeling

To design a controller, an accurate system model is needed. In this task, students are expected to model the system by generating a graph that shows the speed of the motor (output) and applied input signal. The system is modeled as a first-order system; thus, to completely describe the system, gain (K_m) and time constants (τ) must be calculated. Using the gain and time constant, the system is modeled (1). Using the hardware listed above, the time constant (τ_m) and *dc* gain K_m of the model are equal to 1.23 and 0.14, respectively. Figure 4 shows the speed of the motor when the input is applied.

$$\frac{Speed}{V_{input}} = \frac{K_m}{\tau_m s + 1}. \quad (1)$$

c. Task 3: Filter design

Students observe that the motor speed in the previous task is noisy Figure 4. This is due to the discrete nature of the calculations and the resolution of the encoder. Speed is calculated by counting the number of pulses in a specified time window. To improve the appearance of the signal, a digital low-pass filter can be used to remove high-frequency components and smooth the appearance of the signal.

A simple filter can be designed using a pole-zero placement method. A digital low-pass filter is created by placing a zero and a pole at discrete frequencies $\Omega = \pi$ and 0, respectively, as shown in Figure 5a. [26]. The transfer function of the filter is (2):

$$H(z) = k\frac{z+1}{z-a}, \tag{2}$$

where k is chosen equal to $(1–a)/2$ to ensure a unity dc gain. In this work, the filter is given by (3):

$$H(z) = 0.075\frac{z+1}{z-0.85} \tag{3}$$

using bilinear transformation [26], s is replaced by $z = \frac{1+\frac{T}{2}s}{1-\frac{T}{2}s}$, where T is the sampling time. The resulting analog filter is given by (4):

$$H(s) = \frac{1}{1+\frac{s}{\omega_c}} \approx \frac{1}{1+0.07s}. \tag{4}$$

The filter is implemented as a digital filter on the Arduino board, and the equivalent analog filter given above will be used to study the impact of the filter. Figure 5b compares the frequency responses of the analog and digital filters. Figure 6 shows the measured speed before and after the filter. The figure shows the oscillatory speed before the filter and a smooth signal after filtering.

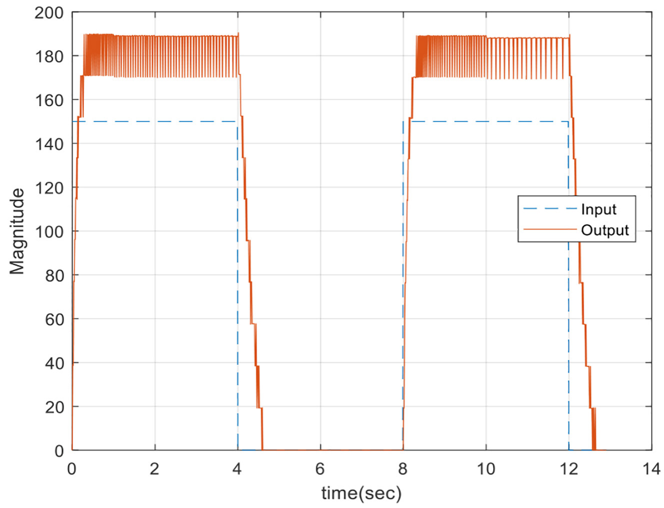

Fig. 4. Input and motor output speed signal signals

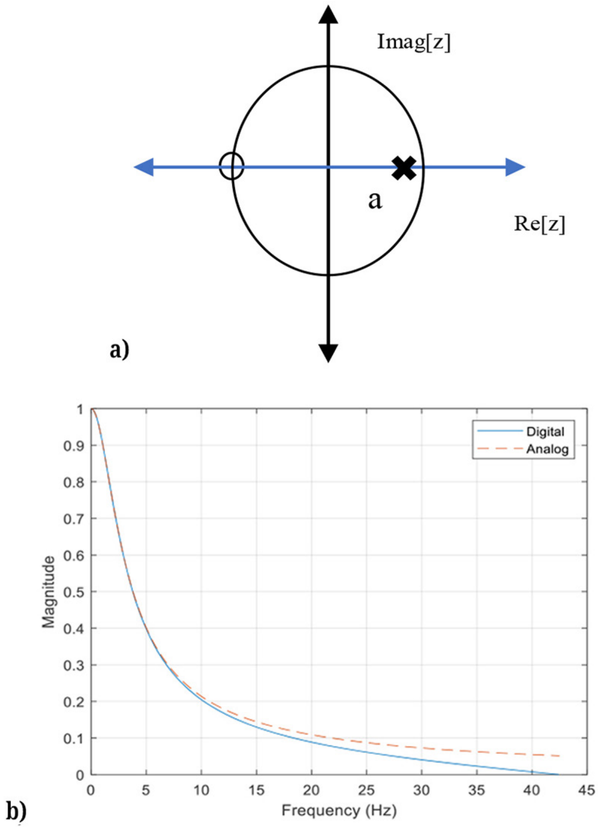

Fig. 5. Filter design using pole-zero placement: (a) pole-zero locations of the digital filter and (b) analog and digital filter responses

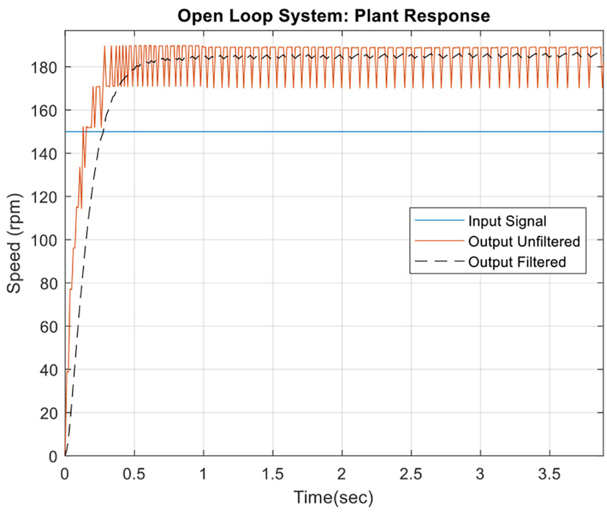

Fig. 6. Input, filtered, and unfiltered speed of the motor

The relationship between the applied voltage and filtered motor speed can be modeled by a second-order system. Using the motor transfer function and the continuous-time equivalent of the digital filter developed above, the overall open-loop transfer function is expressed as:

$$G(s) = \frac{1.23}{0.14s+1} \times \frac{1}{0.07s+1} = \frac{125}{s^2+21.4s+102}. \tag{5}$$

Figure 7 compares the measured and simulated speed based on the open-loop model developed. The figure confirms that the model accurately depicts the output of the system.

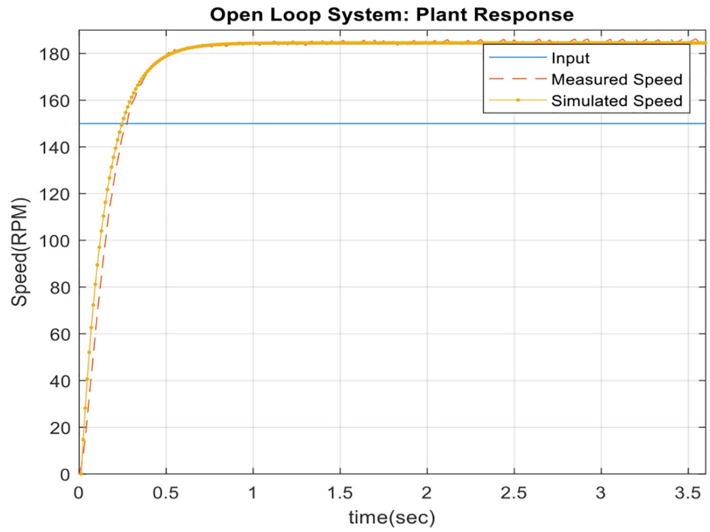

Fig. 7. Measured vs. simulated motor speed based on the developed model

d. Task 4: Analysis and controller design using root locus

With the developed model, the next task is to design different controllers and study their behavior and performance. Before designing any controller, the open-loop system is analyzed. Students are asked to plot the root locus to better understand the system's behavior. As the root locus graph shows in Figure 8, the system behaves as overdamped for small values of gain and underdamped when the gain exceeds 0.0114 [27].

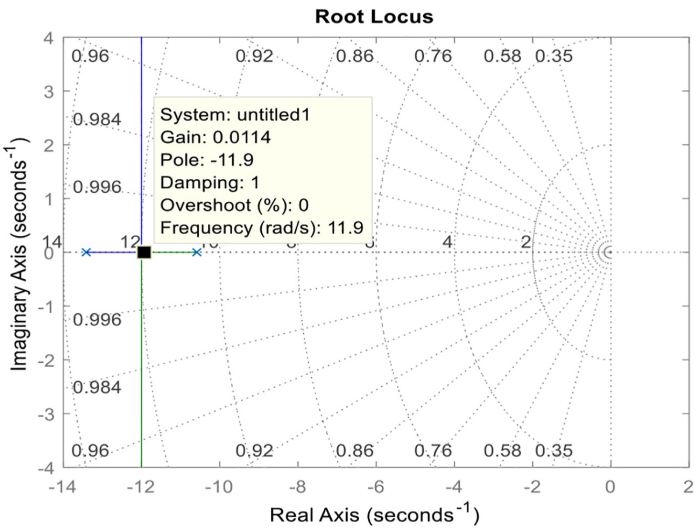

Fig. 8. Root locus of the modeled system

e. Task 5: Controller design

The goal of this task is to design and implement different controllers and observe their impact on the system response. Proportional, proportional integral, and proportional integral derivative controllers are studied. A closed-loop system is established by driving the motor with the signal (error) generated from the difference between the input and the motor speed, as shown in Figure 9. We consider different controllers' implementations:

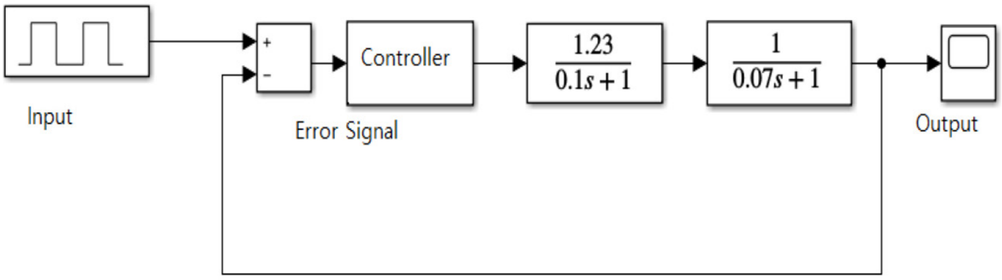

Fig. 9. Closed-loop system

3.1 Proportional controller

The proportional controller is simple. It multiplies the error signal with a gain (K_p) before applying it to the motor. The value of the gain determines the performance of the system and the steady-state error. The closed-loop transfer function can be calculated as (6):

$$T(s) = \frac{1.23K_p}{0.007s^2 + 0.08s + 1.23K_p} \tag{6}$$

Students can observe the impact of increasing the gain on the steady-state error and system response. As Figure 10 shows, when the gain is increased, the steady-state error is reduced, and the system becomes more underdamped. The results show agreement with the simulated results. Students can analytically calculate and verify the steady-state error as well. The students will observe that using a proportional controller alone, it is not possible to eliminate the steady-state error.

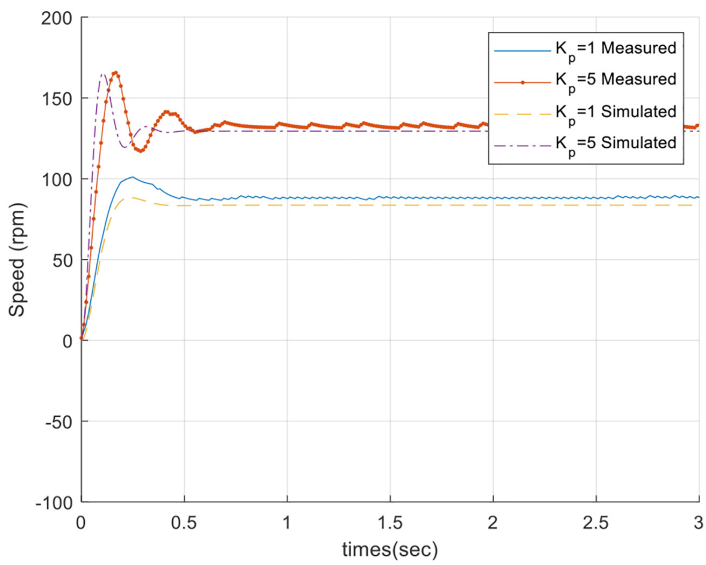

Fig. 10. Simulated and measured speed using a gain controller

3.2 Proportional integral (PI) controller

To reduce steady state error, a PI controller is needed. The PI controller can be expressed as [27]:

$$G_{PI} = k_p + \frac{k_i}{s} = \frac{k_p s + k_i}{s} = \frac{k_p\left(s + \frac{k_i}{k_p}\right)}{s} \tag{7}$$

students can be guided to choosing k_i/k_p to cancel one of the poles of the system *i.e*., choosing the controller zero at $s = 14$ to cancel the plant pole at $s = 1/0.07 = 14$, resulting in a closed-loop transfer function equal to (8).

$$T(s) = \frac{1.23k_p}{0.1s^2 + s + 1.23k_p} = \frac{12.3k_p}{s^2 + 10s + 12.3k_p} \tag{8}$$

The closed-loop transfer function is in a standard second-order format *i.e*.

$$T_{closed\ loop} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \tag{9}$$

The measured and simulated responses of the PI controller are plotted in Figure 11. Students should be able to observe the ability of a PI controller to eliminate steady-state error as shown in the figure.

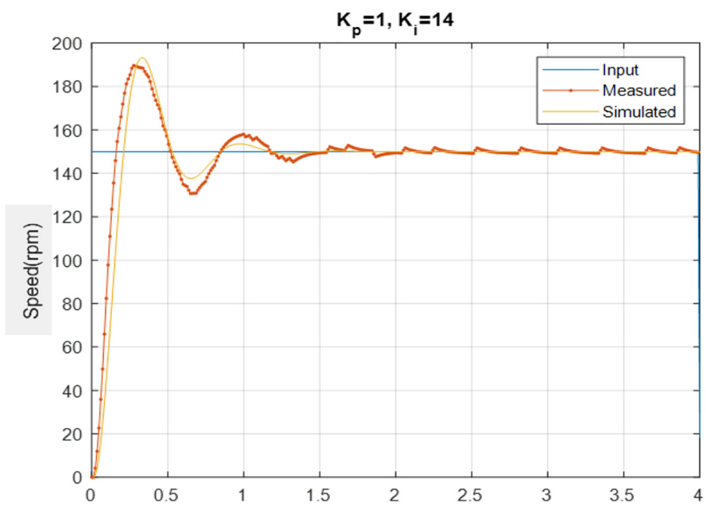

Fig. 11. Response using a PI controller

3.3 Proportional integral derivative (PID) controller

Students can study the effect of the derivative component on the transient response by implementing a PID controller. The expression for a PID controller is given by (10).

$$G_{PID} = k_p + k_d s + \frac{k_i}{s} = \frac{k_d s^2 + k_p s + k_i}{s} \tag{10}$$

Figure 12 shows the response when a derivative component is added to the controller.

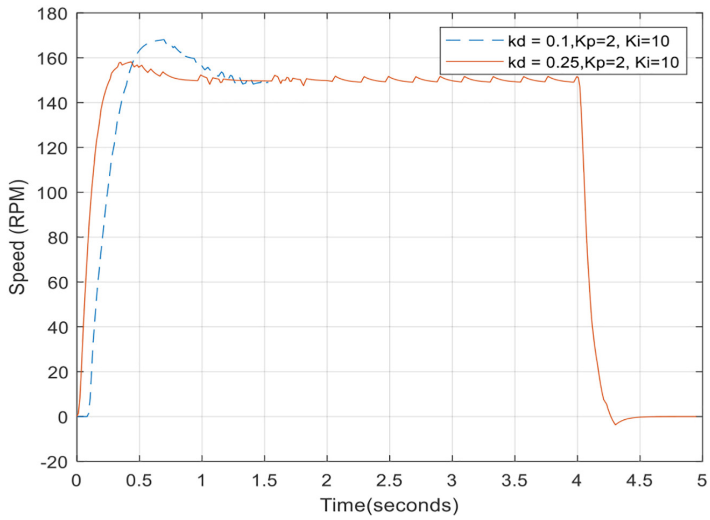

Fig. 12. Response using a PID controller

4 DISCUSSION

This experiment was added to the curriculum in the fall and spring semesters of a linear control lab. In the fall, the experiment was assigned as a project that students completed independently after receiving the hardware components. In spring, the experiment was performed in the lab with more guidance. The experiment can be completed within a 3-hour lab. The students performed analysis and completed the reports afterward.

Following the lab experiment, the students were asked to complete a survey to measure the effectiveness of the project. The students were asked about:

- Reinforcement of concepts learned in class
- Project effectiveness to increase interest in control systems
- Practical problems promoting more interest
- Teamwork

Based on the discussion with students and the student survey (Table 2), many students (a total of 25 students surveyed) enjoyed having a project that involved hardware with a practical application. Many have requested that more hardware projects be added to the lab in the future. They indicated that it helps reinforce concepts and theories from multiple courses and ties the theories easily to a practical application.

Assigning the project in the fall and allowing students to work independently to obtain results worked well for many students. However, some students were not very familiar with Arduino and needed help getting started. This motivated offering the project as a regular lab experiment in the Spring. Having the students perform under the supervision of an instructor removed the anxiety of setting up the hardware and software and getting the experiment started.

Future offerings of the lab will deploy a hybrid model, where students are given the choice of conducting the experiment independently or performing it during a guided lab session. This flexible approach accommodates different learning styles and allows students to engage with the material at their own pace. By providing this option, the lab aims to reduce the anxiety of students who may be unfamiliar with Arduino or hardware setup, giving them the opportunity to build confidence before working hands-on. Additionally, this model fosters a more inclusive learning environment, ensuring that all students, regardless of their prior experience, can successfully develop their skills in software and hardware implementation.

Table 2. Student survey

Item 1	Strongly Agree	Agree	Disagree	Strongly Disagree
The project reinforced concepts learned in class	11	12	0	2
The project raised my interest in Electrical Engineering	8	15	1	1
The project raised my interest in Control Systems	7	13	4	1
Practical engineering problems made the project interesting	17	7	0	1
The project improved my teamwork skills	6	18	1	0

5 CONCLUSION

This study introduces a project-based learning approach that was incorporated into a control systems course. The primary objective is to develop a practical project that reinforces the concepts learned in control systems, signal processing, and programming. The project employs low-cost components to design, construct, and analyze controllers for regulating motor speed. Students are highly motivated by the hands-on aspect of the task, as well as applying theoretical concepts to achieve tangible results. The paper provides an overview of both the theoretical background and specific tasks related to this project.

The project was offered for two semesters, and student feedback was collected. Students were excited by the practical nature of this project, which helped them reinforce their understanding of theories. Overall, student feedback has been overwhelmingly positive.

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