BRIDGING THEORY AND PRACTICE: A LABORATORY SEQUENCE FOR AUTOMATIC CONTROLS EDUCATION

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Bridging Theory and Practice: A Laboratory Sequence for Automatic Controls Education

Abstract

This paper presents a three-part laboratory sequence designed to bridge the gap between the mathematical rigor of automatic control theory and the practical skills required to develop and implement a feedback control system. The laboratory immerses students in a realistic development scenario centered on the design of an automatic door system. Framed as a hypothetical yet authentic engineering application, the project requires students to complete (1) analytical system modeling, (2) experimental model validation, and (3) real-time controller implementation.

In the first phase, students develop a theoretical actuator–plant model and design a closed-loop controller in simulation, which is tuned to meet preliminary performance objectives. The second phase emphasizes experimental validation, during which students test the physical hardware to refine model parameters, characterize feedback sensor behavior, and identify potential nonlinear effects such as dead-zones (biases) and saturation (thresholds). The validated model is then used to re-tune and verify the controller in simulation. In the final phase, students implement their closed-loop control system on the physical hardware under more demanding performance requirements, including precise door position tracking. Achieving these objectives requires students to design custom time-based reference trajectories to replace the step inputs commonly used during controller tuning.

Assessment of student performance is based on the accuracy of the identified system models, the ability of the designed controllers to meet specified performance criteria, and the successful execution of the real-time control implementation. The laboratory sequence provides a cohesive, hands-on progression from theoretical modeling to hardware deployment, reinforcing core feedback control concepts while emphasizing model-based design and analytically driven engineering decision making. The sequence has been implemented successfully over multiple semesters, with assessment results and instructor observations indicating high student engagement and consistent attainment of the intended learning outcomes.

Nomenclature

Parameters used in this document:

- J mass moment of inertia
- B rotational viscous damping
- L armature inductance
- R armature resistance
- n gear reduction ratio
- Θ angular position
- V_a armature voltage
- K_t DC motor torque constant
- K_b DC motor back emf constant
- K_{ss} steady-state gain
- ω_n natural frequency
- ζ damping ratio

Introduction

The subject of automatic controls continues to grow in importance across a variety of engineering disciplines. Technological advancements in electronics, computing, and sensor technology have enabled feedback control to be integrated into a continually expanding range of products and systems. Despite these developments, introducing feedback control concepts to undergraduate engineering students remains a persistent pedagogical challenge. In particular, helping students grasp how a closed-loop system uses feedback to adjust process outcomes toward a desired state often proves conceptually difficult in early controls education.

While textbook models and computer-based simulations offer a solid theoretical framework for constructing and analyzing feedback systems, a well-documented gap remains between these introductory exercises, and a practical understanding of how such systems are applied in real-world engineering contexts. This issue is not unique to control systems education but is a common challenge throughout engineering curricula, where bridging the divide between theory and professional practice remains a critical educational goal.

To help close this gap, a variety of low-cost, hands-on instructional platforms have been developed over the past two decades. Early efforts included microcomputer-based DC motor speed control systems designed for undergraduate electric machinery laboratories [1], followed by portable, at-home controls laboratories [2,3] and microcontroller-based control experiments [4]. More recent initiatives have emphasized affordable, student-kits that enable the exploration of feedback control principles beyond the confines of the traditional laboratory [5–7]. These systems, often incorporating DC motors, inverted pendulums, and electromechanical devices, give students opportunities to design, test, and validate controllers while engaging directly with physical hardware.

A notable example is the development of a low-cost DC motor system by Cook et al. [7], which integrates hardware-in-the-loop (HIL) simulation and allows students to perform hands-on feedback control exercises both inside and outside the laboratory. Similarly, Rodriguez et al. [8] introduced a multifunctional hydraulic motion control trainer designed to reinforce control concepts in fluid power applications, offering students the opportunity to investigate control dynamics in physical systems, compare theoretical predictions with experimental results, and to educate students about the benefits and capabilities of fluid power.

Building on these established instructional efforts, the present work seeks to enhance students' comprehension of control theory by developing a laboratory experience centered on a hypothetical, everyday application familiar to students. By contextualizing control exercises within relatable scenarios, this approach aims to further bridge the gap between abstract theoretical concepts and practical engineering problem-solving, ultimately improving students' ability to transfer classroom knowledge to professional engineering contexts.

Methods

In this work, the authors present a three-part laboratory sequence designed to engage students in the development and implementation of a control system, framed within a hypothetical industrial project scenario. The lab sequence immerses students in a workflow that mirrors the staged, iterative process common in control system development. The structure is as follows:

Part 1: Development of Actuator-Plant Model
Recognizing that control system development often begins before hardware is available, this stage focuses on modeling, analyzing, and simulating a DC motor-actuated swinging door with position feedback control. A plant model is constructed using hypothetical open-loop dynamic response data, and students learn to tune control gains to meet target performance specifications through simulation.

Part 2 Open-loop Dynamic Response Experiments with Swinging Door System
Once hardware is introduced, students conduct open-loop response tests, refining the hypothetical model based on data gathered from physical system behavior. The updated model is then used to further adjust control gains in preparation for the final implementation phase.

Part 3 Implementation and Product Demonstration
The combination of analytical modeling and experimental testing in the first two parts prepares students to implement their control system on an Arduino-based real-time hardware-in-the-loop platform. At this point, students are presented with final response requirements and tasked with customizing the controller's reference signal to achieve the desired performance. Delaying the disclosure of these precise motion specifications encourages students to focus their early efforts on establishing a well-tuned, stable closed-loop system before tackling the final operational objectives.

This three-week laboratory sequence effectively guides students through a structured yet practical control system development process. The continuity of the project and its contextual storyline deepen students' understanding of how automatic control principles and iterative development are applied in real-world scenarios.

Unlike some of the more prescriptive lab exercises within the course, this sequence incorporates significant guided student engagement, requiring students to make decisions, analyze results, and refine their work iteratively. This approach reinforces a systematic design methodology while providing opportunities for applied problem-solving within a realistic engineering context.

PART 1: Development of Actuator-Plant Model

The laboratory sequence begins with the modeling, analysis, and simulation of a DC motor-driven swinging door system using theoretical open-loop dynamic response data. After determining the model characteristics from the response data, this phase concludes with the implementation of a simulated feedback control system, which must be tuned to meet a specified set of performance requirements.

A key component of this stage is reviewing the development of the theoretical model for the plant being controlled. Building on students' prior experience with dynamic modeling of DC motors and mechanical systems, this activity extends their understanding by incorporating a gear reduction into the motor model, better reflecting the physical system used in the laboratory. To reinforce students' proficiency with block diagrams, the activity also challenges students with reducing the block diagram of the motor-door system, as shown in **Figure 1**. The objective is to determine the overall plant transfer function and, in the process, develop an understanding of the system's order and expected dynamic behavior.

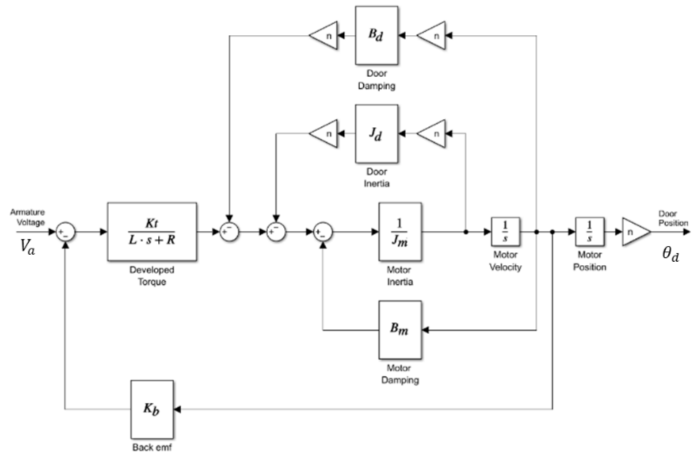

Figure 1: *actuator-plant model*

The resulting transfer function describing the motor-door dynamics is:

$$\frac{\Theta_d(s)}{V_a(s)} = \frac{nK_t}{LJ_e s^3 + (RJ_e + LB_e)s^2 + (RB_e + K_t K_b)s} \quad (1)$$

where the effective inertia J_e and damping B_e experienced by the motor are determined by the combined inertia and viscous damping of the motor (J_m, B_m), and the door J_d and B_d and are expressed as:

$$J_e = J_m + n^2 J_d \text{ and } B_e = B_m + n^2 B_d \quad (2)$$

From (2) the students are reminded that the gear reduction ratio of $n < 1$ serves to reduce the impact of the door's inertia and damping on the motor. From the derived motor-door transfer function in (1), nine model parameters are required to fully characterize the theoretical system. However, the structure of the transfer function offers useful insight for experimental identification, revealing that only three generic model coefficients are necessary. To enable this simplification, the transfer function can be reduced to a minimal form by factoring out an s-term and the leading denominator coefficient:

$$\frac{\Theta_d(s)}{V_a(s)} = \frac{K_{ss}\,\omega_n^2}{s(s^2 + 2\zeta\omega_n s + \omega_n^2)} \quad (3)$$

With varying levels of guidance, students are led to recognize this as a second-order system in angular velocity, with an additional integrator resulting in third-order behavior in angular position. This understanding naturally leads to the idea that experimentally capturing the system's response can enable identification of classical dynamic properties: *natural frequency*, *damping ratio*, and *steady-state gain*.

To gain experience with system identification, students are tasked with analyzing the provided hypothetical dynamic test data in **Figures 2–4** to estimate the parameters in the reduced transfer function model. **Figure 2** presents the excitation voltage input pulse applied to the motor, while

Figure 3 shows the resulting position response of the door and **Figure 4** displays the corresponding velocity response. The intended outcome is for students to determine the system's basic response characteristics from the second-order velocity response, then validate their plant model by comparing simulated performance results to the open-loop dynamic response data provided. Specifically, they will simulate the system's response to the same voltage pulse and assess whether their simulated position and velocity outputs match those shown in **Figures 3** and **4.**

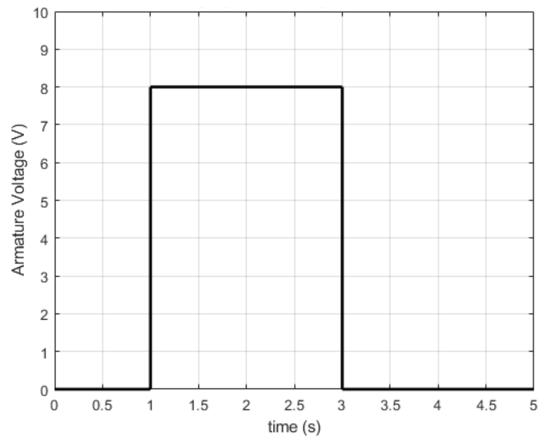

Figure 2: *Swinging door excitation voltage pulse*

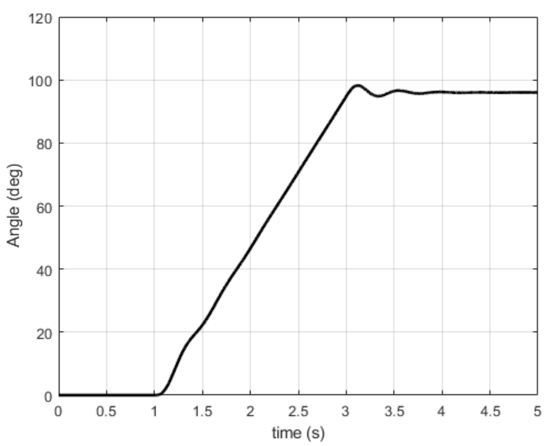

Figure 3: *Swinging door position response to voltage pulse*

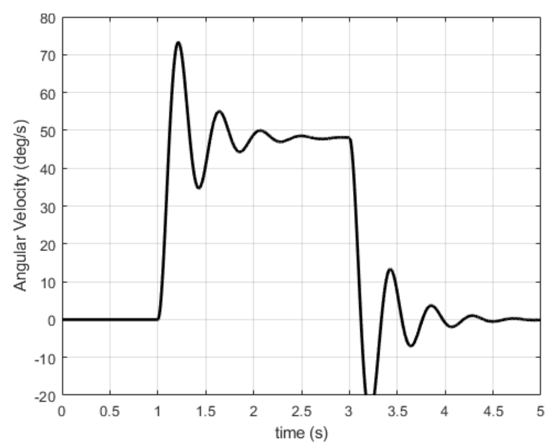

Figure 4: *Swing door velocity response to voltage pulse*

Once the estimated model parameters are validated, students implement position feedback control using a PID architecture to meet specified transient and steady-state step response criteria. They develop a closed-loop control system designed to move the door to a specified target position. Specifically, students are tasked with commanding the door to open to 90° and tuning their controller gains to minimize the 2% settling time while keeping the response overshoot below 5%. This hands-on experience involving system parameter identification, closed-loop control implementation, and controller tuning prepares them for the next phase, where they apply the same workflow to the physical hardware.

Part 2: Open-loop Dynamic Response Experiments for Swinging Door System

Students extend their learning by conducting open-loop dynamic response experiments on a benchtop scale-model of an industrial door. This physical system consists of an 80/20-framed door actuated by a DC motor, with position measurements provided by an encoder and control implemented via an Arduino microcontroller with Simulink support.

Experimental Swinging Door System

The swinging door hardware system used for the laboratory sequence is shown in **Figure 5**. The design philosophy behind this test apparatus was to create a relatable, hands-on application featuring a system that is underdamped and exhibits relatively linear behavior in both its sensor feedback and mechanical dynamics. These objectives were largely achieved. One simple enhancement currently being considered is adding mass to the swinging door to further reduce system damping, a feasible modification since the motor is sufficiently sized to handle the increased load.

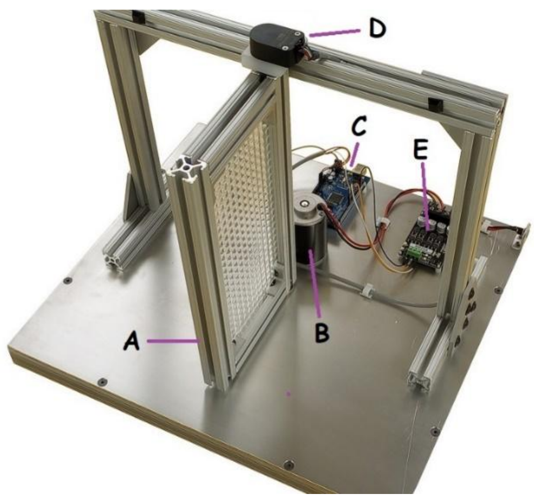

Figure 5: *Automatic door hardware*

The system consists of several key components working together to enable controlled motion and position feedback. These components are summarized below:

System Components:

- **Swinging Door (A)**: The plant, or object to be controlled. A rigid body with a mass moment of inertia rotating about a fixed axis at the hinge.
- **Armature-Controlled DC Motor (B)**: Drives the door via a 3:1 pulley reduction system mounted beneath the platform.
- **Arduino-MEGA Controller (C)**: Interfaces with the optical encoder for position feedback and executes control logic generated in Simulink. Outputs the control signal (direction and magnitude) to the motor control board.
- **Optical Encoder (D)**: Produces 500-count-per-revolution quadrature signals for position feedback, which are read by MEGA controller.

- **Motor Control Board (E)**: Supplies the physical voltage to the DC motor, enabling controlled door motion.

A detailed list of the main hardware components used for the construction of the Door Assembly is provided in **Table 1.** The components are widely available and are relatively low cost.

Table 1. *Part List and Cost for Door Assembly*

Description	**Cost ($)**
Arduino Mega 2560 R3	50
Cytron Motor Driver MD20A	21
XIN DA 12V DC Motor XD-3420	25
3:1 Pulley & belt set	7
US Digital E5-500-315-IE-S-D-D-B Enconder	50
9V AC/DC Switching Adaptor Power Supply	20
Misc Hardware Costs -80/20 Aluminum with fasteners -1/4” Aluminum baseplate -Wiring -Door hinge bearings -Custom 3D printed mounting brackets -Custom machining	(unknown)
Total	**~$173**

Model Parameter System Identification

In this stage, students experiment with different input signals to characterize the unique dynamics of their door system, identifying key parameters and observing system nonlinearities. The objective is to replace the hypothetical response data from Part 1 with experimentally obtained characteristics, refining the system model for improved feedback control design.

For physical testing of the swinging door, students were provided with a user-friendly Simulink model capable of generating voltage pulses with adjustable magnitude and duration. Because of the physical system’s positional constraints, a conventional step response test was not suitable. Instead, students were tasked with selecting pulse parameters that would move the door at least 90° without contacting the far bumper stop. Avoiding bumper contact was critical, as it would prevent measurement of the door’s natural frequency, a key factor in validating system dynamics.

Before conducting response tests, students performed basic calibration exercises to convert position encoder pulse counts into engineering units (degrees). The test model was then updated to display and record responses in these more convenient units.

A significant challenge in this system identification process was the nature of the velocity signal derived from the hardware. While the optical encoder provided a high-resolution position signal, obtaining velocity required discrete differentiation, which introduced noise and artifacts. As a result, students needed to creatively interpret or filter the data — a process complicated by the need to account for additional filter dynamics when extracting model parameters.

An important additional outcome of working with the hardware was the identification of voltage dead zones and saturation limits within the motor-drive system. These findings were used to augment the motor-door plant model, further improving the simulation's accuracy and fidelity.

Enhanced Simulation Model System Tuning

To complete the second part of the project sequence, students update their control system simulation model based on the response characteristics observed during physical testing. At this stage, the model is further refined by incorporating known system nonlinearities, such as actuator saturation and voltage dead zones, to better align the simulation with the behavior of the hardware.

With these updates improving the model's fidelity, students adjust their control gains to restore the desired response performance. Using this enhanced model, they redesign and tune a PID controller to meet the specified transient and steady-state criteria, while addressing new challenges introduced by the physical system's limitations.

This iterative process of model refinement, control adjustment, and system identification provides valuable experience in translating simulation-based control designs to practical hardware implementations, preparing students for the final phase, where feedback control is deployed directly on the physical system.

Part 3: Implementation and Product Demonstration

The laboratory sequence concludes with students implementing their closed-loop control system on the physical hardware. After refining their model and tuning the controller in simulation, students now face enhanced performance requirements, which include precise position tracking and motion constraints. To meet these demands, they must replace the standard step inputs used in simulation with custom reference signals, challenging them to design motion profiles that are both achievable and hardware friendly. This final stage reinforces their understanding of model fidelity, control design trade-offs, and the practical realities of real-world implementation.

To emphasize that step responses are primarily suitable only for baseline system analysis, the performance specifications for this final exercise are framed in terms of the actual time-history of an automatic door opening and closing scenario. By withholding these final specifications until this stage, students have focused their earlier efforts on refining closed-loop performance. As a result, they enter this phase with a well-behaved control system, capable of tracking any reasonable motion profile — one now shaped independently of earlier feedback system design considerations.

The final task involves developing and implementing a model-based command profile, defining a reference input signal for the control system, and evaluating system performance against a detailed set of motion specifications. These specifications are presented as follows:

Control Performance Specifications:

a. Before starting the controller, manually move the door to the clockwise bumper position.
b. Hold the door at the bumper until the controller starts operating, then release it before $t = 1$second, when the motion sequence is specified to begin.
c. Starting at $t = 1$ s, the door should open to $90° \pm 2°$ before the 6-second mark ($t = 6$ s) and remain within that tolerance until the 10-second mark ($t = 10$ s).
d. The maximum allowable overshoot during the opening phase is 5 degrees.
e. At this time, the door should return to and remain in contact with the clockwise bumper before the control model stops at $t = 20$ s. The impact speed when contacting the bumper should not exceed 5 deg/s.
f. The speed of the door should never exceed 25 deg/s.

Implementation Process:

Starting with a generic open-loop model to drive the hardware and capture position data, students modify the simulation model to implement their closed-loop controller. This involves:

- *Converting the encoder signal* to degrees using the conversion factor established during the prior lab exercise.
- *Adding feedback* and implementing their selected controller — a PID architecture in this case — using previously predicted gains. This step introduces students to key considerations for applying integral and derivative control in a digital environment.
- *Creating a custom reference signal* to match the time-history motion profile outlined in the specifications. This is achieved using one of Simulink's signal-building tools, enabling students to tailor the door's motion commands to meet the defined criteria.

Through this hands-on implementation, students gain valuable experience in bridging the gap between simulation and hardware, applying theory in a practical context, and confronting the complexities of real-world control system deployment.

Results and Discussion

The following outlines a representative progression of student work when the laboratory sequence is approached as intended. It illustrates how students move through each phase of the project, from theoretical modeling and system identification to controller design, simulation refinement, and final hardware implementation.

Developed Model of the Hypothetical System

From the hypothetical response data provided in the first week of the sequence, the students can identify the actuator-plant transfer function characteristics, mostly from the second-order velocity response. They can then build an open loop model and test it with the known voltage pulse to see if they have captured the characteristics correctly.

With an acceptable door model, their next task is to set up a closed-loop control system, implementing PID control. The model is tested for the appropriate general behavior before using the model to tune the PID gains for a successful response, one that meets reasonable target response specifications for a step change in the commanded position. **Figure 6** contains the expected control system model including an appropriate estimate of the hypothetical door model.

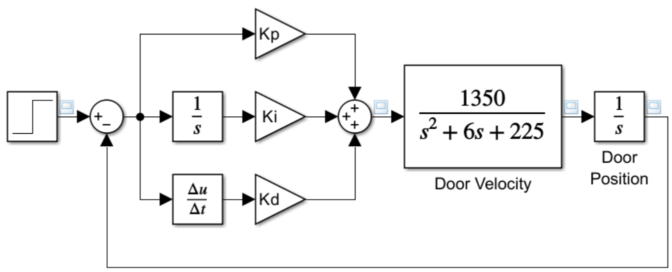

Figure 6: *Representative PID control system with door model*

Physical Testing to Refine the Plant Model

In the second phase of the three-part sequence, the students acquire physical data to better characterize the simulation model. This includes obtaining time response data of the door position and velocity to a known voltage pulse. This requires them to adjust both the magnitude and duration of the pulse to get a sufficient angular response of the door without hitting the far (180-degree) bumper stop.

Other aspects of the student activity during this physical testing are:

- Recording observations to define how the encoder counts are converted to degrees.
- Doing low-voltage trials to identify the voltage dead zone (thresholds) for motion.
- Recording the voltage saturation limits employed in the control hardware.

Figures 7-9 represent a sample of the experimental data collected during physical testing.
Figure 7 shows the excitation voltage pulse applied to the motor, while **Figure 8** and **9** present the corresponding door position and velocity response, respectively.

One successful approach to interpreting the data is to focus on the free response that occurs at the cessation of the voltage pulse. This provides a clearer view of the damped natural frequency and damping ratio from the velocity response, albeit with consideration of the discretized nature of the data. Since the velocity does not reach steady state during the voltage pulse, the students can tune the steady-state gain of the velocity transfer function to achieve a good fit based on the position response.

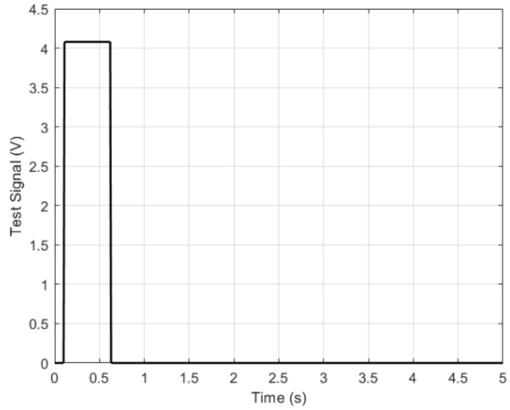

Figure 7: *Experimental motor voltage excitation applied during door testing*

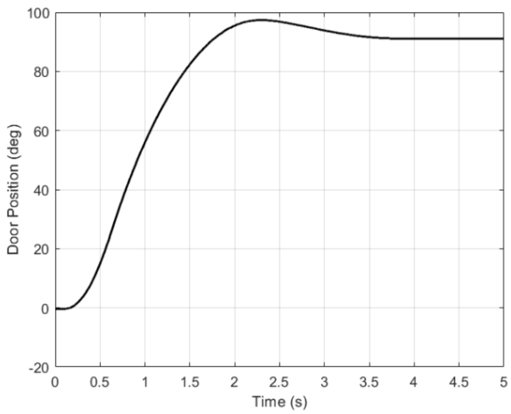

Figure 8: *Experimental door position response*

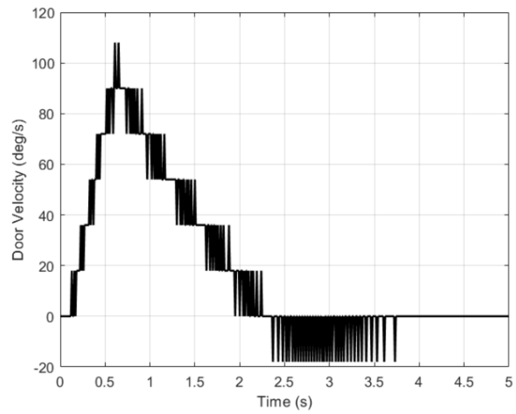

Figure 9: *Experimental door velocity response*

Out of the physical testing, the students have information to update their plant model and to add the appropriate saturation and dead zone elements to their simulation models. **Figure 10** shows an example of an updated simulation model. The students used such a model to further understand the performance of the system and obtain better PID control gains for the swinging door in preparation for their final activity—implementing feedback control on an automatic door scenario.

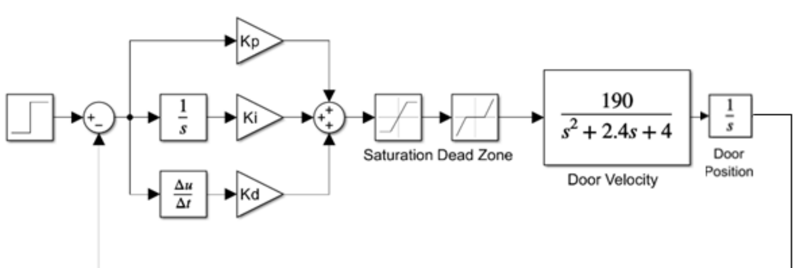

Figure 10: *updated simulation model*

Automatic Door Demonstration

The final phase of the three-part laboratory sequence provides students with the opportunity to implement their planned control strategy within a Simulink-based real-time control environment. As described in the Methods section, students develop a command sequence that satisfies the specified system requirements. This phase is intentionally structured to guide students in replacing the step position commands used during controller tuning with desired time-based motion profiles.

Several student groups demonstrated foresight by validating their motion planning strategies within the simulation environment prior to gaining access to the physical hardware. This practice reinforces a central theme of the laboratory sequence: the importance of analytically based engineering design and verification before hardware implementation.

Student Performance and Observations

Across the two most recent course offerings (approximately 20 students per cohort), 100% of student teams successfully completed the full three-laboratory sequence. Final scores ranged from approximately 80% to 100%, with class averages consistently in the high 80% to low 90% range. This performance is attributed in part to the collaborative nature of the laboratory activities and to structured instructor guidance provided during implementation.

Performance deductions were most associated with incomplete documentation or presentation quality rather than conceptual misunderstandings. Student engagement remained high throughout the sequence, particularly during the final automatic door demonstration. While some groups encountered challenges related to system nonlinearities, such as stiction or mechanical misalignment, these difficulties served as productive learning opportunities. With targeted coaching, students were able to adjust controller gains and achieve satisfactory performance.

Future work will incorporate more individualized assessment strategies and student perception surveys, pending appropriate IRB approval, to better evaluate learning outcomes. Overall, the results indicate that the proposed laboratory sequence provides a robust, replicable hardware-based platform that effectively integrates modeling, simulation, and control implementation within a modern control systems course.

Limitations

While the results demonstrate the effectiveness of the laboratory sequence and platform, several limitations should be acknowledged. First, assessment of student learning outcomes in this study is primarily based on group performance, instructor observation, and completion rates rather than individualized, quantitative measures of learning gains. As a result, the extent to which each student independently achieved the learning objectives cannot be fully isolated. Future offerings will incorporate individual assessments and student perception surveys, subject to appropriate IRB approval, to provide more granular evaluation.

Second, the mechanical system exhibits inherent nonlinearities, including stiction, backlash, and variability due to component wear and assembly tolerances. Although these effects intentionally expose students to real-world challenges, they can introduce inconsistencies across laboratory stations and cohorts. Continued refinement of the hardware and calibration procedures will help improve repeatability while preserving instructional value.

Finally, the current implementation has been evaluated within a single institutional context and course structure. While the platform is designed to be low-cost and replicable, broader adoption across different curricula and instructional settings has not yet been formally studied.

Conclusion

This three-part laboratory sequence effectively guided students through a realistic control system development process within a three-week laboratory experience. The continuity of the project and its hypothetical yet authentic context engaged students in a cohesive demonstration of how dynamic system modeling, experimental validation, and automatic control design can be integrated into a practical engineering application. By progressing systematically from analytical modeling to real-time hardware implementation, students developed hands-on proficiency in system identification, controller design, and the evaluation of real-world engineering trade-offs.

The immersive, model-based structure of the laboratory reinforced core feedback control concepts while emphasizing analytically driven design and verification prior to hardware deployment. Assessment of student work, including the accuracy of identified models, controller performance relative to specified criteria, and successful real-time implementation, indicates that the majority of student teams achieved the intended learning outcomes. Although the project initially presents a significant challenge, students increasingly demonstrate confidence as they recognize how individual elements of the control design process align and contribute to a functioning system.

The laboratory sequence has been implemented successfully over four consecutive semesters, with consistently high levels of student engagement and control implementations that largely meet faculty-defined performance expectations. While assessment in this study is primarily group-based and limited to a single institutional context, the results demonstrate that the proposed laboratory sequence constitutes a robust and replicable hardware-based platform for control systems education. Future work will focus on developing more rigorous, individualized assessment instruments, including targeted student surveys and quantitative performance metrics, to more comprehensively evaluate student learning and further support the instructional observations associated with this laboratory experience.

Acknowledgements

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References

[1] Nehrir, M. H., Odermann, A. J., and Bowen, B. D., 1990, “A Microcomputer-Microprocessor-Based DC Motor Speed Controller for Undergraduate Electric Machinery Laboratory,” IEEE Trans. Educ., 33(4), pp. 341–345.

[2] Durfee, W., Li, P., and Waletzko, D., 2005, “At-Home System and Controls Laboratories,” ASEE Annu. Conf. & Expo., Portland, OR.

[3] Jouaneh, M., and Palm, W., 2010, "System Dynamics and Control Take-Home Experiments," ASEE Annu. Conf. & Expo., Louisville, KY.

[4] Gunasekaran, M., and Potluri, R., 2012, "Low-Cost Undergraduate Control Systems Experiments Using Microcontroller-Based Control of a DC Motor," IEEE Trans. Educ., 55(4), pp. 508–516.

[5] Reck, R. M., and Sreenivas, R. S., 2015, "Developing a New Affordable DC Motor Laboratory Kit for an Existing Undergraduate Controls Course," Proc. 2015 American Control Conf., pp. 2801–2806.

[6] Schinstock, D., Schinstock, S., and White, W. N., 2015, "Microcontroller-Based Update of Inexpensive Undergraduate Control Systems Laboratory Hardware," Proc. 2015 American Control Conf., pp. 2807–2812.

[7] Cook, M. D., et al., 2020, "Low-Cost DC Motor System for Teaching Automatic Controls," Proc. 2020 American Control Conference, Denver, CO, USA, pp. 4283–4287.

[8] Rodriguez, L. A., et al., 2019, "Development of a Motion Control Laboratory Focusing on Control Design and Fluid Power Education," ASEE Annu. Conf. & Expo.