AC 2012-3183: USB-POWERED PORTABLE EXPERIMENT FOR CLASSICAL CONTROL WITH MATLAB REAL-TIME WINDOWS TARGET

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USB-Powered Portable Experiment for Classical Control with Matlab Real-Time Windows Target

Abstract

Engineering education has the objective of not only presenting the scientific principles, i.e., engineering science, but also of teaching students how to apply these to real problems. Therefore, hands-on laboratories have been an integral part of the engineering curriculum since its inception. This presentation will demonstrate the use of a novel low-cost experimental apparatus for use in a typical undergraduate course in control systems taught to mechanical engineering students, i.e. students with limited exposure to electrical engineering. The system demonstrates the use of MATLAB tools such as Simulink Real Time Windows Target and Control Systems toolboxes to illustrate all stages of design of a closed-loop control systems including: system modeling, parameter identification, analysis of stability of a closed-loop system, design of dynamic compensator in the continuous space and implementation of an equivalent digital controller using the Simulink Real Time Windows Target environment. The hardware apparatus consists of a DC micro-motor attached to a carbon fiber rod. The angular displacement is measured with an analog potentiometer, which acts as the pivot point for the carbon fiber rod. The DC micro-motor is powered by a low cost, custom circuit board, which is USB-powered requiring no external power adaptor or extra cabling. Attached to the micro-motor is a small propeller which provides thrust force needed to rotate the pendulum to a desired angle. The experiment is designed to operate from student's laptops, therefore no special laboratory space is required.

The project was tested in a classical control systems design class offered to senior-level mechanical engineering students. Student feedback and survey data on the effectiveness of the module are presented along with examples of student assignments illustrating the use of hardware.

Introduction

Hands-on laboratories have been an integral part of the engineering curriculum since its inception. Their importance has been recognized by the Accreditation Board of Engineering Education (ABET) and its predecessors by creating criteria requiring adequate laboratory practice for students[1-4]. During the last three decades, engineering laboratories have become more complex, including simulation tools and computer controlled test and measurement equipment. This increased sophistication has also led to more expensive equipment[5,6].

The inclusion of such laboratory courses in the undergraduate curriculum is challenging due to the large number of students and the increased demand for instruction and equipment time. Hands-on experience, on the other hand, is invaluable for active and sensory learning styles, which are the predominant types of learning styles used by undergraduate students[9-12]. This paper describes the development and testing of a new low-cost take-home laboratory module designed to supplement the experience of our students taking their first course in Controls System Design.

While there are many turn-key desktop systems designed to illustrate controls systems courses, portable kits, such as Arduino are primarily designed for mechatronics and embedded computing courses[13,14]. As such, they require programming environments, installation of additional software, and additional plug-in modules for operating DC motors and other actuators. Furthermore, unless one uses advanced circuit boards and processors, implementing a PID or other dynamic compensators is cumbersome and requires training in digital control and programming. With the emergence of the Matlab Simulink graphical programming environment, modeling and simulation of various plants and controllers can be accomplished quite easily by students who might not have extensive training in digital control and numerical methods. However, practical implementation of such controllers remains elusive for most undergraduate students outside of electrical and mechatronics departments. Therefore, the objective of this project was to develop a simple physical plant that can be used seamlessly with the Simulink Real-Time Windows Target environment to allow students who are not in electrical engineering programs to implement and test real-time controllers using drag-and-drop style graphical programming.

The target audience for the experiment was primarily students who are not electrical engineering majors, as these students typically do not have the benefits of electronic circuits training and tend to shy away from projects involving electronics. In the Aerospace and Mechanical Engineering Department of The University of Arizona, it is not unusual for the Control System Design course to have enrollment of about 100 students. This makes offering a laboratory section within the course nearly impossible. The project described here was developed primarily as a way to provide some practical experience to the students using an inexpensive and portable setup which can be taken home. The portability and low-cost of the setup allows them to conduct experiments during the semester and use the device to complete a term project. In addition to significantly reducing the cost of offering an experimental component, the experimental module provided an opportunity to demonstrate a modern approach towards control systems based on computers (digital control).

Description of Hardware Apparatus

The experimental setup consists of a small electric motor driven by a 5 V pulse-width modulated (PWM) signal. The motor is attached to the free end of a light carbon rod, while the other end of the rod is connected to the shaft of a low-friction potentiometer. The potentiometer is fixed on a plastic stand at the proper height, so that the pendulum can swing freely (see Fig. 1). A 2-in propeller (model U-80) is attached to the motor shaft to produce a thrust force in order to control the angular position of the pendulum. The portability of the kit is enhanced by an innovative design allowing the kit to be shipped in a flat 2-in-thick box as shown in Fig. 1(left). A fastener-free design allows the kit to be assembled into its operating condition by interlocking three acrylic plates which interlock when rotated by 45 degrees with respect to the base plate as shown in Figure 1(right). A self-calibrating step during the initialization allows the system to automatically find the vertical position (origin of the coordinate system). A custom designed circuit board produces the controlled voltage supply for the motor via Pulse-Width Modulation (PWM) with a resolution of 0.05 V. It also reads out the voltage on the potentiometer, which is proportional to the angular position of the pendulum. These functions are implemented using a Freescale MC9S08JM16 microcontroller. The apparatus communicates with the controlling computer (PC, Mac, or Linux) using the USB protocol, eliminating the need for the increasingly harder to find serial port. The device is powered by two USB ports, capable of providing a total of 600mA from the host computer. While the motor is capable of producing high rate of revolution in excess of 15,000 rpm, its current consumption is below 500 mA with typical values in the 200-300 mA range. This allows USB-based operation without the need for an external power supply. The microcontroller is commanded to apply various PWM signals to appropriate sides of the H-bridge IC (two P-MOS, two N-MOS) driver depending on the desired direction. When queried, the microprocessor returns the result of several averaged twelve-bit analog to digital conversions to MATLAB, which is then correlated through a proportionality constant to the angle of the pendulum.

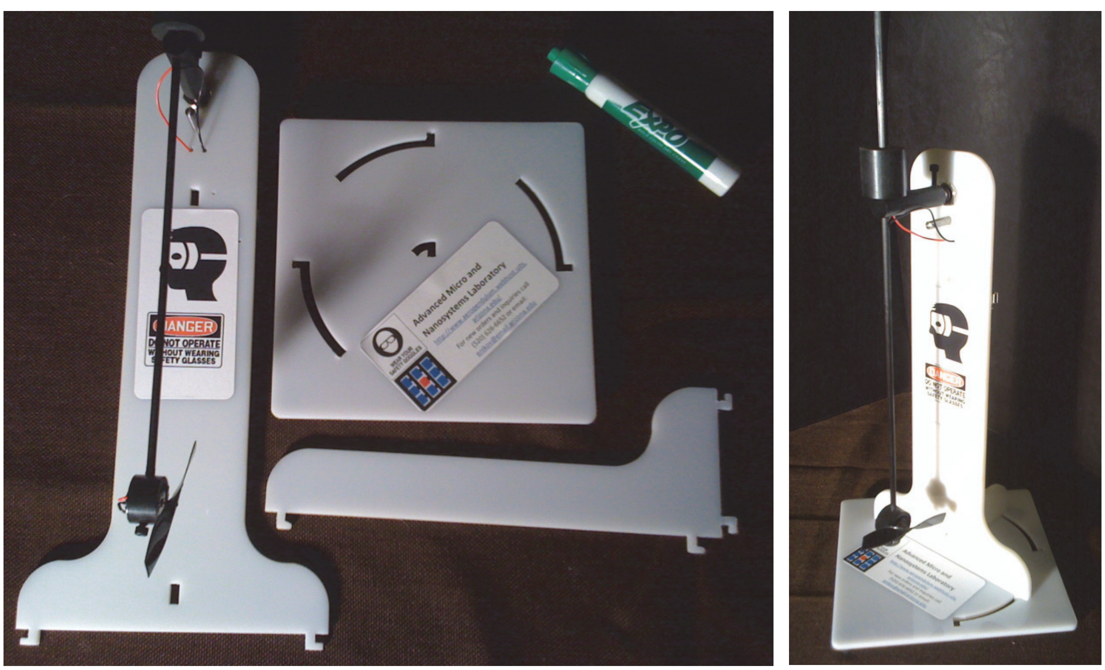

Figure 1. Aeropendulum Kit: Flat Configuration for During Shipping (left); Operating Configuration (right)

Matlab Simulink Control Environment

The aeropendulum control environment can operate in real-time using Matlab/Simulink Real Time Windows Target (RTW) environment (see Fig. 2).The RTW module performs classical control experiments using hardware in the loop simulations. Using RTW, the sampling time was reduced by an order of magnitude to 5 ms. This is achieved by a built-in functionality of RTW that compiles the Simulink model down to C or C++ code, and then builds a native executable file. Alternatively, a slower controller operating at 100 ms update rate can also be used with systems without RTW tool box as described on the project website[15].

To receive the angle of the pendulum, the microcontroller must be asked to send the angle. This is a done via Packet-Out blocks. Once the data is ready, the Packet-In block receives the raw voltage. A step function with a period of 5ms and a duty cycle of 50% is used to generate a query to the microprocessor every 5 ms.

Using "Controller Select" switch, students are able to select between four modes of operation: open loop control (1); proportional control (2); lag controller (3); and lead controller (4). The lag and lead controllers reference discrete transfer functions defined in Matlab's workspace. In a typical offering of the experiment, the parameters of these controllers are detuned thus forcing the students to carry out the design activities and select appropriate transfer functions.

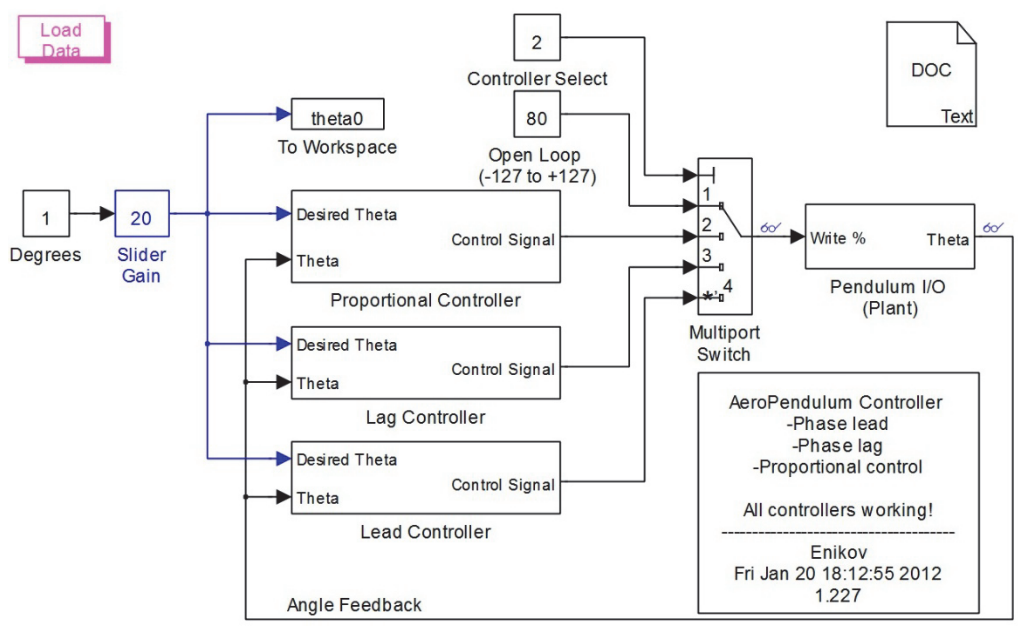

Figure 2. Simulink Controller

Design Activities

The hardware described here has been tested by senior-year mechanical and aerospace engineering students taking their first course in controls system design. Prior to this experiment this course has been a lecture-only class, therefore the experiment had to be conducted as part of the regular homework assignments. Typically, students receive the aeropendulum kit at the beginning of the semester and are asked to work independently or in groups of two or three students.

The first assignment is to develop a mathematical model of the pendulum using conservation of linear momentum about the pivot point. The students are asked to focus on the dynamics of the pendulum, while the dynamics of the electronic components and the DC motor were assumed fast and negligible for the sake of this step. Most students correctly report an equation of motion given by

$$mL^2\ddot{\theta} = -mgL\sin\theta - c\dot{\theta} + TL\,, \tag{1}$$

where mg is the weight of the motor, L is the length of the rod, c is the viscous friction coefficient, and T is the thrust force from the propeller. The students are instructed to assume a proportionality law between the propeller thrust, T, and the applied motor voltage v

$$T = \kappa v\,.$$

The target board converts these to a motor voltage according to $v = 5u/127$, where the factor 5 is the supply voltage of the USB port. Therefore, the thrust force is proportional to the PWM sent by Matlab RTW module, u

$$T = \kappa v = \underbrace{\kappa\frac{5}{127}}_{K}u = Ku \tag{2}$$

The second assignment contains an experimental task to examine the steady-state behavior of system (1)-(2) and to determine some of its parameters. To this end, students apply a range of input values $u_{ss} \in [0;127]$ and plot the sine of the steady-state pendulum angle expecting to find a plot representing

$$\sin\theta_{ss} = \frac{K}{mg}u_{ss}\,.$$

A typical experimental plot is shown in Figure 3. While the plot is quasi-linear, it shows that for small input values, the motor is unable to overcome the static friction and a dead-zone exists in the range $u_{ss} \in [0;20]$

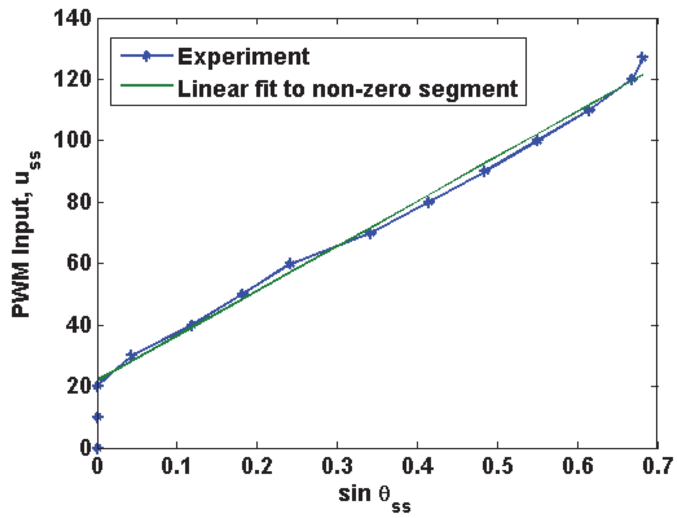

Figure 3. Steady-State Response for Different Inputs Levels

This presents the first challenge in dealing with real systems. At this stage, students are instructed to use a non-linear law in the form

$$u = \begin{cases} \bar{u} + 20, \text{if } \bar{u} > 0\,; \\ \bar{u} - 20, \text{if } \bar{u} < 0, \end{cases} \tag{3}$$

and to verify that it cancels out the dead-zone in terms of the new input signal $\bar{u}$

$$mL^2\ddot{\theta} = -mgL\sin\theta - c\dot{\theta} + KL\bar{u}. \tag{4}$$

Upon completion of this task, students are asked to verify that a non-linear feedback law in the form of

$$\bar{u} = \frac{mg}{L}\sin\theta + w \tag{5}$$

will also linearize the plant (3) by cancelling $-mgL\sin\theta$ producing a linear system described by a second order transfer function

$$\frac{\Theta(s)}{W(s)} = \frac{KL}{mL^2 s^2 + cs}\,. \tag{6}$$

Using Simulink RTW environment, it is straightforward to implement the suggested feedback laws (3) and (4) as illustrated in Figure 4.

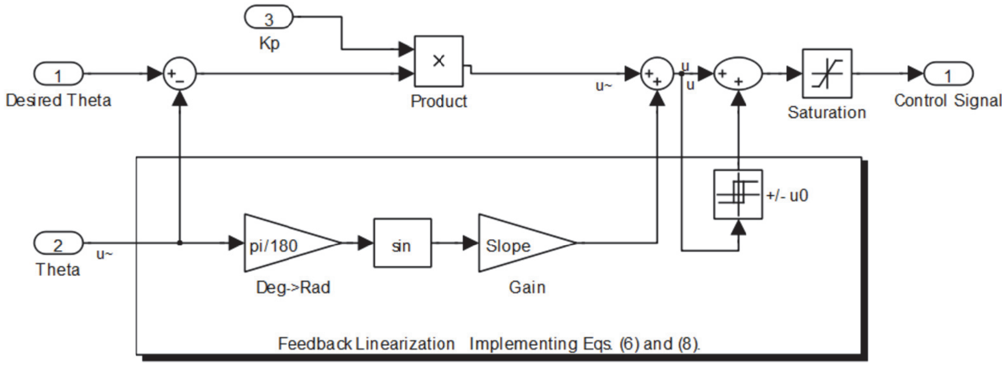

Figure 4. Implementation of Non-Linear Feeback Linearization Laws

In the third installment, students are asked to identify the dynamic characteristics of a unit-feedback system formed from around the plan (6). This task is designed to illustrate the application of the classical formulas describing the natural frequency and damping ratio of a second order system. Since the feedback-linearized system (6) is of type 1, its open-loop step response is unbounded. Therefore, a unit-feedback proportional controller is used to examine the response of the closed loop system as illustrated in Figure 5.

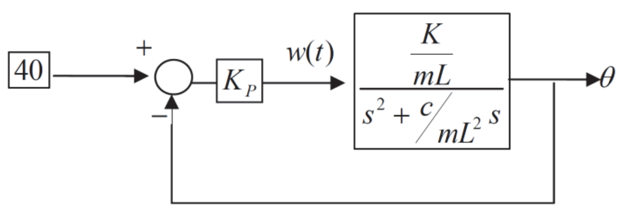

Figure 5. Unit-Feedback Unit-Gain (*Kp*=1) Controller for Plant (6).

Under this task, the students are asked to derive formulas for the natural frequency and damping ratio of the system in Figure 5 for $K_p = 1$ and to obtain values of the model parameters from the step response of the plant through the formulas they have derived

$$\omega_n^2 = \frac{K}{mL}$$

$$2\xi\omega_n = \frac{c}{mL^2}.$$

Upon completion of the initial parameter estimation, students are able to examine the stability predictions of the model by varying the gain K_p. Contrary to what they would expect based on the theory of second order systems, the plan has a critical gain $K_p^* \approx 3$, beyond which the system loses its stability as illustrated in Figure 6.

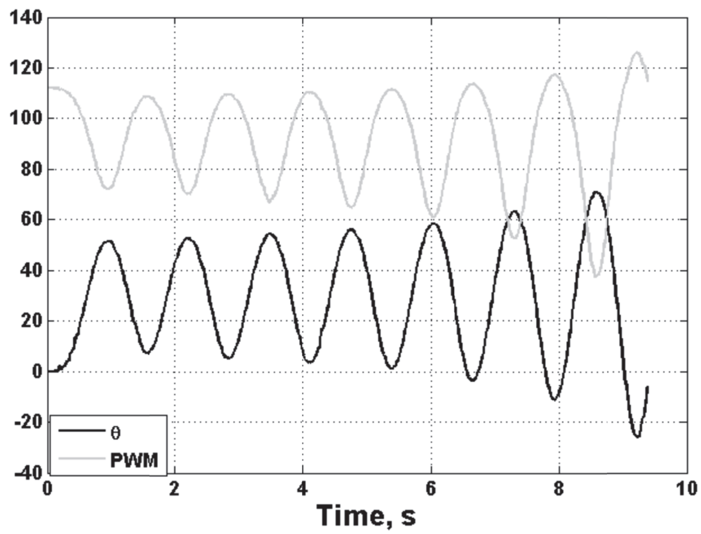

Figure 6. Unstable System Response for *Kp*=3.

The observed instability is easy to explain when considering the dynamics of the motor-rotor sub-system. The motor represents an additional second-order system for two additional state variables (current and rate of rotation). When considered in the model, the fourth order system does indeed have a stability limit, which presents an opportunity to refine the model by adding a critically damped pole-pair at $-1/T_D$ and adjusting the value of T_D until the critical gain of the model coincides with the experimentally observed one.

After the addition of the critically damped pole-pair, the students have a reasonably accurate model which allows them to carry out dynamic compensator design. In their final project installment, they are asked to design a lag compensator in the form

$$C_{lag} = \frac{s+z}{s+p}, \qquad z > p > 0$$

with the goal of reducing the steady-state error caused by the imperfect feedback linearization. With proportional control alone, students often report steady-state errors of 3-5 degrees, which are most likely due to thermally induced parameter drift. In this project installment, the students are asked to reduce the plant's steady-state error below 1 degree, which leads to a requirement to increase the DC gain by a factor of 5. Therefore, the lag controller with $z = 5p$ is selected. The only remaining parameter to tune is the value of p, which students select using either root locus or Bode plot design methods. Prior to testing, the lag controller has to be converted to z-domain using a command mode continuous to discrete transformation command *c2d,* which is part of the Control Systems Toolbox, (*Clagd=c2d(Clag,0.01,'zoh')* . The newly defined *Clagd* is referenced by the Lag Controller block of the Simulink RTW model. To activate input from this block, students also need to set the input selector value to 3 (see Fig. 2). The resulting response of the plant is shown in Figure 7, where two manually induced disturbances are also visible. As anticipated, the steady-state error is below 1 degree and it can be noticed that the integrator term reduces the error over approximately 20-second period which matches the time constant of the pole *p*=0.05. In a similar way, the students can design and implement lead, lead-lag, and notch compensators of any order.

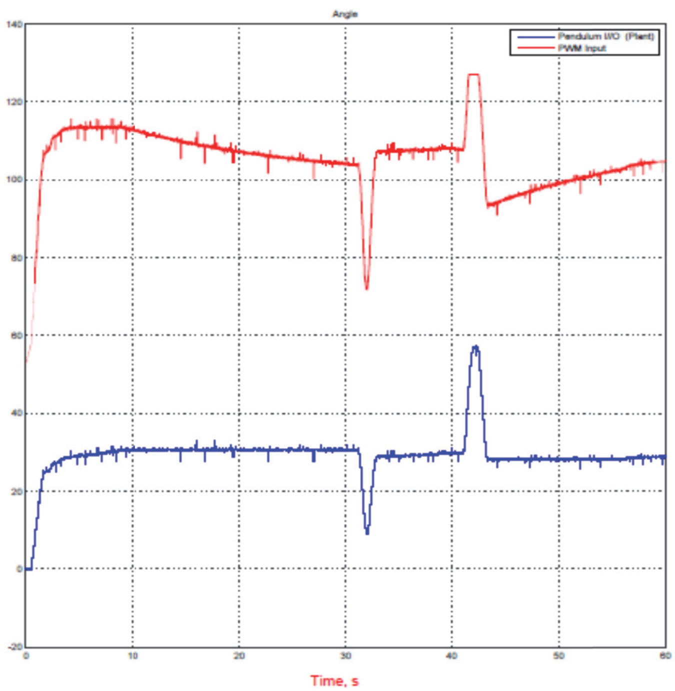

Figure 7. Aeropendulum Step Response to a Reference Input of 30 with a Lag Compensator *z*=0.25, *p*=0.05.

Project Evaluation

During the 2008-2011 academic years, the project was offered several times to three different cohorts and by different instructors. The impact of the project was assessed through student surveys conducted at the end of the course following the protocol approved by the Institutional Review Board. Additional data were drawn from student reports. The data reported here (see Table 1) are from a section not taught by any of the authors; instead the instructional materials and hardware were provided to a different instructor and his teaching assistant. However, the results from surveying the authors' sections agree to within 5%-8% in most categories of the data shown here. As part of the evaluation, students were asked questions about the technical content, as well as the implementation and impact of the portable experiment. The highest benefits are derived from better understanding of the relationships between stability and gain, the importance of transfer functions in capturing the physical models, followed by the ability to deal with non-linear systems and time delay. Interestingly, the highest gains (average rating of 3.32 in Table 1) were achieved in understanding of the relationship of stability and gain. When asked to comment on the discrepancy observed between the theory and experiment in a homework-style assignment, 33% of the students correctly identified the missing rotor dynamics as a possible cause, while 56% felt that the feedback linearization somehow masked the unstable modes or was imperfect, leading to loss of stability. Another 11% looked for physical limitations in the system or faulty components. It appears that the large number of misconceptions paired with challenging the students' confidence in their ability to model the plant, along with providing a plausible solution to the problem, could explain the highest gains in this category. Further case studies would be required to confirm this observation. Among the least understood topics was the use of Bode plots, perhaps due to the fact that it was covered at the very end of the semester, leaving little time for practice and exploration.

Table 1 Student Feedback Data

To what extent (how well) did the project illustrate the following technical concepts?

	Not at all	Less than expected	More than expected	Very Well	Rating Average*
Relationship between physical system and transfer function	0.0% (0)	7.1%(2)	64.3%(18)	28.6%(8)	3.21
Second-order system response	3.6% (1)	10.7%(3)	60.7%(17)	25.0%(7)	3.07
Relationship between stability and gain	0.0% (0)	10.7%(3)	46.4%(13)	42.9%(12)	3.32
Relationship between overshoot and gain	3.6% (1)	25.0%(7)	35.7%(10)	35.7%(10)	3.04
Use of root locus	0.0% (0)	17.9%(5)	57.1%(16)	25.0%(7)	3.07
Use of Bode plots	14.3% (4)	39.3%(11)	35.7%(10)	10.7%(3)	2.43
System type and steady state error	7.1% (2)	10.7%(3)	50.0%(14)	32.1%(9)	3.07
Disturbance rejection and system recovery	7.4% (2)	11.1%(3)	48.1%(13)	33.3%(9)	3.07
Non-linearities and ways to deal with them	0.0% (0)	14.3%(4)	60.7%(17)	25.0%(7)	3.11
Effects of time delay	0.0% (0)	17.9%(5)	53.6%(15)	28.6%(8)	3.11

* Point scale: 1 - Not at all, 2- Less than expected, 3- More than expected, 4- Very well

The portability and convenience of the implementation of the experiment was evaluated through a second set of questions, where 42.9% of the students reported that they did not need a permanent lab and another 42.9% had to use a teaching assistant consultation for not more than 1 hour. Only 3.6% of the respondents to this question indicated that more consultation was needed, while 10.7% wanted to have a permanent lab space dedicated to the project. The average duration for completion of the project was 7.78 hours.

Conclusions

An inexpensive portable experimental setup has been described for use as a hands-on experience for undergraduate students taking senior-level classical control system design courses. The project requires minimal or no supervision without the need for a specialized laboratory space. In 10 out of 11 topics, students self-reported above average learning gains. Highest gains were achieved through a problem that challenges the student's trust and beliefs in the theory when confronted with an apparent contradiction with experimental observations. Presenting the project as a series of short assignments allows the instructor to provide guidance to the students without sacrificing the ability to encourage individual experimentation. The project is particularly aimed at students whose major is not electrical engineering becoming familiar with the modern developments in implementation of real-time control systems. While simple, the hardware allows demonstration of advanced concepts such as feedback linearization. Evaluation data show that the project is well-received among students and it can be completed independently over an average of 8 hours. Parameter variation through modification of the configuration of the pendulum allows the instructor to individualize each kit.

Acknowledgments

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