Mechatronic Aeropendulum: Demonstration of Linear and Nonlinear Feedback Control Principles With MATLAB/Simulink Real-Time Windows Target

Eniko T. Enikov, *Member, IEEE*, and Giampiero Campa, *Member, IEEE*

***Abstract*—This paper presents a low-cost hands-on experiment for a classical undergraduate controls course for non-electrical engineering majors. The setup consists of a small dc electrical motor attached to one of the ends of a light rod. The motor drives a 2-in propeller and allows the rod to swing. Angular position is measured by a potentiometer attached to the pivot point. A custom-designed circuit board produces the controlled voltage input to the motor. The target board is powered and communicates with the PC through its USB port using a virtual RS-232 port. A simple MATLAB/Simulink module has been created to read the pendulum angle and send a command signal to the motor. The module is based on Real-time Windows Target software, which allows a sampling rate of up to 200 Hz. Students are able to design and test classical PID and phase lead-lag controllers, as well as modern controllers, including state-space controller design combined with feedback linearization. A semester-long series of assignments is described that can be carried out without the need for a specialized laboratory or teaching assistants. The project was tested in a classical control systems design class of senior-level mechanical engineering students. Student feedback and survey data on the effectiveness of the modules are also presented.**

***Index Terms*—Feedback linearization, linear feedback control, real-time control, real-time windows target, Simulink.**

I. Introduction

HANDS-ON laboratories have always been an integral part of the engineering curriculum. Their importance has been recognized by the Accreditation Board of Engineering Technology (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 [5], [6]. This increased sophistication has also led to more expensive equipment [7], [8]. The inclusion of such laboratory courses in the undergraduate curriculum is challenging, due to the large numbers of students and the increased demands 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 exhibited by undergraduate students [9]–[12]. This paper describes the development and testing of a new low-cost portable laboratory module, designed to supplement the experience of 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 advanced circuit boards and processors are used, 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 illusive for most undergraduate students outside of electrical and mechatronics engineering programs. 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.

In the Department of Aerospace and Mechanical Engineering of The University of Arizona, Tucson, it is not unusual for the Control System Design course to have enrollments of over 100 students. This makes offering a laboratory section within the course nearly impossible. The experiment described here was developed primarily as a way to provide some practical experience for students, using an inexpensive and portable setup that can be taken home. The experiment was developed following the principles of the variational theory of learning developed by Marton and coworkers [15], [16] and the approach of guided discovery/interactive-engagement labs characteristic of several well-known labs, such as the Modeling Workshop Project [17], Socratic Dialogue Inducing Labs [18], Real Time Physics [19], and Tools for Scientific Thinking [20]. The portability and low cost of the setup allowed the students to conduct experiments during the entire semester and use the device to complete a term project. In addition to significantly reducing the cost of offering

Manuscript received September 29, 2011; revised January 27, 2012; accepted March 30, 2012. Date of publication May 01, 2012; date of current version October 26, 2012. This work was supported by the NSF under Grants 0856761 and 0927661

E. T. Enikov is with the Department of Aerospace and Mechanical Engineering, College of Engineering, University of Arizona, Tucson, AZ 85721 USA (e-mail: enikov@email.arizona.edu).

G. Campa is with Mathworks, Inc., El Segundo, CA 90245 USA.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TE.2012.2195496

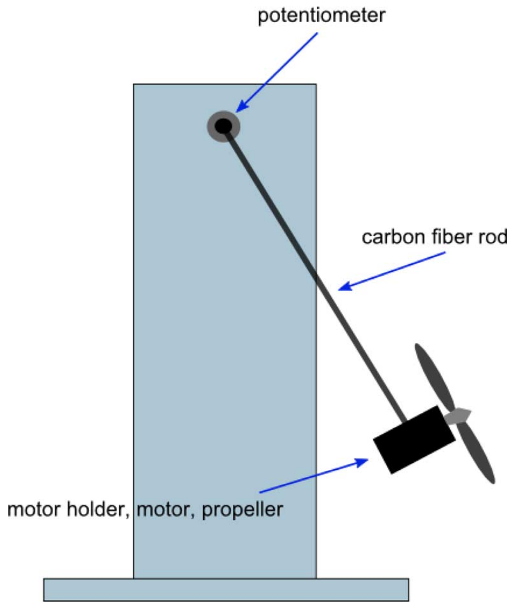

Fig. 1. Aeropendulum: dc-motor/propeller-driven pendulum.

Fig. 2. Target board.

Fig. 3. Adjustable pendulum with counterweight.

an experimental component, the experimental module provided an opportunity to demonstrate concepts from system identification, nonlinear feedback control, and digital control.

II. Hardware Description

A. Aeropendulum

The setup consists of a small dc 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 a height where 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. A self-calibrating step during the initialization allows the system to automatically find the vertical position (origin of the coordinate system).

B. Target Board

A custom-designed circuit board produces the controlled voltage supply for the motor via PWM with a resolution of 0.05 V (see Fig. 2). It also reads 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 an increasingly rare serial port. The device is powered by two USB ports that are capable of pulling a total of 600 mA from the host computer. The microcontroller is commanded to apply various PWM signals to appropriate sides of the H-bridge IC drives (two P-MOS, two N-MOS, ZETEX ZXMHC10A07T8TA), depending on the desired direction. When queried, the microprocessor returns the average of several 12-bit analog-to-digital conversions to MATLAB, which is then correlated through a proportionality constant to the angle of the pendulum.

In its latest implementation, the aeropendulum kit has been modified to include a movable counterweight and variable length rod, as shown in Fig. 3. This simple modification allows the instructor to adjust the inertia of the pendulum, as well as the required feedback linearization action, and thus produce an individualized setup for each student.

C. Simunlink Environment

The experiment also illustrates the use of the MATLAB/Simulink Real-Time Windows Target (RTW) environment (see Fig. 4). 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 was 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. Removing the need for an interpreter greatly improves the efficiency of the simulation. Packet-In and Packet-Out blocks are used in the RTW model to communicate with the microcontroller. The Packet-Out

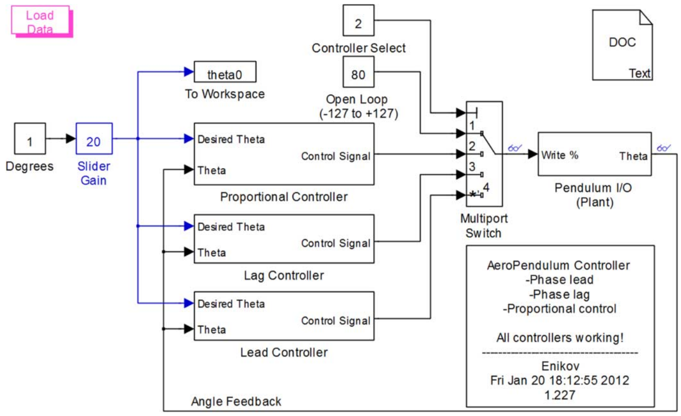

Fig. 4. Simulink Real-Time Windows controller.

block is used to send a request for data to the microcontroller. Once the data are ready, the microcontroller sends the data to the Packet-In block. A step function with a period of 10 ms and a duty cycle of 50% is used to generate a query to the microprocessor every 10 ms.

III. Student Experiments

A. Modeling

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 had been a lecture-only class, so the experiment had to be conducted as part of the regular homework assignments. Consequently, the students had to be given a detailed manual on how to install the kit.[1] The project assignment asks the students to develop a nonlinear mathematical model of the pendulum and identify its physical parameters. The students focus on the dynamics of the pendulum. (The dynamics of the electronic components and the dc motor are assumed fast and negligible for the sake of this experiment.) Typically, the students arrive at

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

where mg is the weight of the motor, L is the length of the pendulum, c is the viscous friction coefficient, and T is the thrust force from the propeller. The students then model the resulting thrust force as a linear function of the applied voltage, u, using a thrust coefficent K

$$T = Ku \tag{2}$$

resulting in a modified model

$$mL^2\ddot{\theta} = -mgL\sin\theta - c\dot{\theta} + K\,Lu. \tag{3}$$

Students are next asked to examine the steady-state behavior of the plant (3). Quick analysis leads to a method for extracting the

[1]http://nano.arizona.edu/pages/education/micro-mechatronics-and-controls-experiment1.php

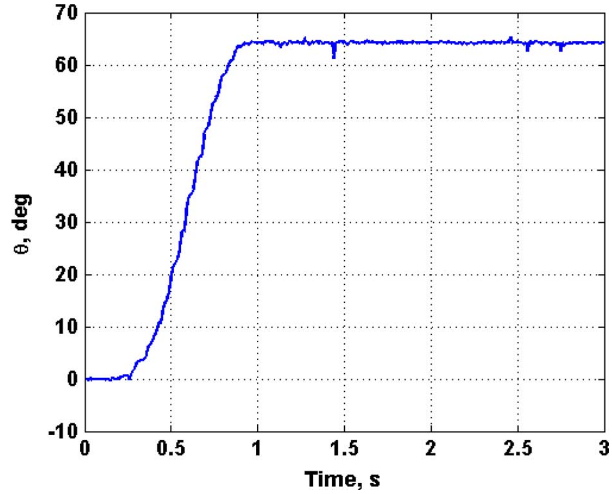

Fig. 5. Open-loop response.

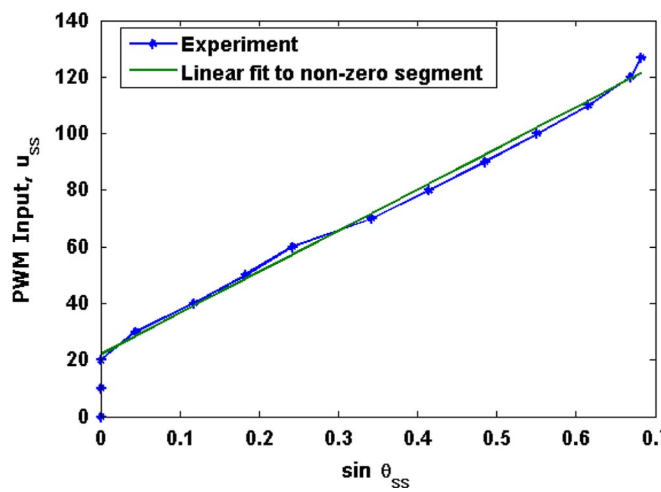

Fig. 6. Input signal (PWM) versus sine of steady-state angle.

value of the parameter K/mg by noting that the steady-state angle θ_{ss} and the steady-state input u_{ss} are related through

$$\sin\theta_{\text{ss}} = \frac{K}{mg}u_{\text{ss}}. \tag{4}$$

B. Feedback Linearization

In their second assignment, students are asked to carry out experiments and verify (4) experimentally. A typical experimental plot is shown in Fig. 5. Using multiple input values, students obtain pairs of steady-state angles and input voltages, as shown in Fig. 6. This plot presents an opportunity to observe a non-ideal behavior associated with real systems. The motor exhibits a dead-band, i.e., for voltages below approximately 1 V (20% of 5 V), the propeller does not turn due to friction. The modified model for the thrust force is therefore

$$T = \begin{cases} K_+(u-u_0), & \text{if } u > u_0 \\ 0, & \text{if } u \in [-u_0, u_0] \\ -K_-(u+u_0), & \text{if } u < -u_0. \end{cases} \tag{5}$$

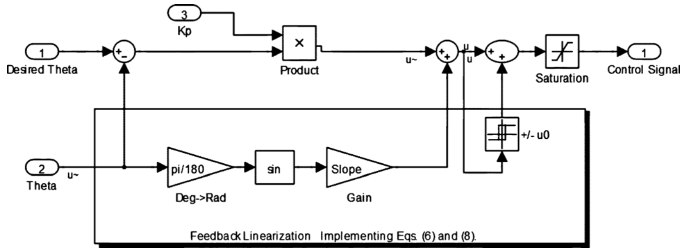

Fig. 7. Implementation of feedback linearization according to (6) and (8).

Coefficients K_+ and K_- correspond to positive and negative input voltages and are different due to the asymmetry of the propeller operation. Using this model and experimenting with positive and negative inputs, the students determine approximate values of these coefficients extracted from a bidirectional version of the plot in Fig. 6

$$\frac{K}{mg} = \frac{K_+}{mg} = \frac{2K_-}{mg} = \frac{1}{145}$$

where the factor 2 reflects the experimentally observed fact that the propeller is twice as efficient in the forward direction as in the reverse direction $(K_+ = 2K_-)$. The next step is to eliminate the observed dead-band. To this end, the students are instructed to use a discontinuous control law

$$u = \begin{cases} \bar{u} + u_0, & \text{if } \bar{u} > 0 \\ \bar{u} - u_0, & \text{if } \bar{u} < 0 \end{cases} \tag{6}$$

which has the effect of canceling the dead-band region. As is evident from Fig. 6, the approximate value of u_0 is 22. The resulting model in terms of the new input variable $\bar{u}$ is

$$mL^2\ddot{\theta} = -mgL\sin\theta - c\dot{\theta} + K\,L\bar{u}. \tag{7}$$

Finally, the feedback linearization is achieved through the use of a nonlinear feedback in the form

$$\bar{u} = \frac{mg}{K}\sin\theta + w \tag{8}$$

which cancels out the nonlinear term. The resulting linear system has a simple transfer function with two real poles at 0 and $-c/mL^2$, respectively

$$\frac{\Theta(s)}{W(s)} = \frac{KL}{mL^2s^2 + cs}. \tag{9}$$

Implementation of the nonlinear feedback linearization represented by (6) and (8) is shown in Fig. 7. Since the propeller is more efficient in the forward direction, only positive command signals are considered, and elimination of the dead zone is reduced to addition of the offset u_0. The cancellation of the effect of gravity is accomplished by the addition of $mg\sin\theta$. The resulting linearized system is a classical one (presented in all textbooks on controls) and is easy to relate to the associated lectures.

The final step in developing the plant model is to identify the parameters of (9). Due to the integrator term (pole at zero), the system is of type 1 and will produce an unbounded response if tested with a step input. Another interesting observation students make is that when $\tilde{u} = 0$, the pendulum is "weightless" due to feedback linearization. It is easy to show that under such conditions $\theta = \text{const}$ is a solution to (9). Therefore, if the pendulum is manually pushed to a particular angle, it remains there due to the automatic adjustment of power according to (8). Fig. 8 demonstrates the corresponding response. If the feedback linearization is not perfect due to errors in the parameter estimation, the pendulum will have the tendency to droop or rise, which is easy to observe visually.

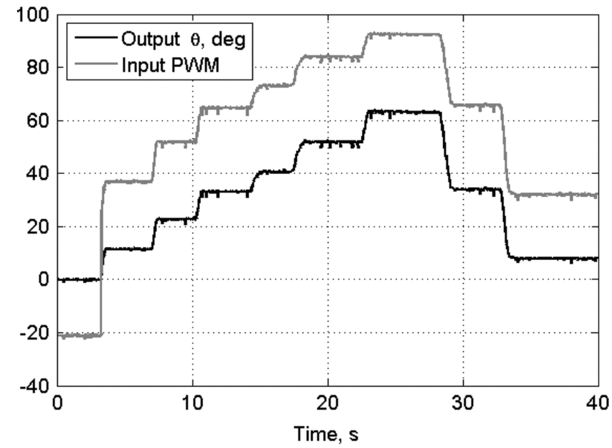

Fig. 8. Feedback-linearized pendulum ("weightless") response.

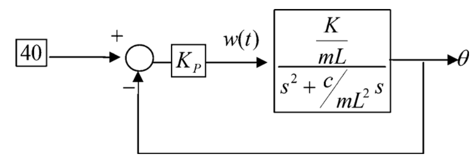

Fig. 9. Closed-loop system.

C. System Identification of Linearized Plant

As a third assignment, the students are asked to identify the system type of the linearized plant (9). Generally, steady-state errors and associated system types are covered early in the semester, therefore this step tends to serve as a reminder and illustration of a known material. Typically, students recognize the type-1 behavior and correctly expect to see a zero or negligible steady-state error. The suggested approach is to implement a unit-feedback control of (9) by setting

$$w = K_p(\theta_0 - \theta) \tag{10}$$

with $K_p = 1$. The resulting block diagram is shown in Fig. 9. Students then use the step response of this system to identify the values of the parameters K/mL and c/mL^2 by deriving the following formulas relating the natural frequency ω_n and damping ζ of a second-order system to the physical parameters of the model:

$$\omega_n^2 = \frac{K}{mL}$$
$$2\zeta\omega_n = \frac{c}{mL^2}. \tag{11}$$

A sample experimental plot of the step response for a command input of 40 degrees is shown in Fig. 10. Through this experiment, the students are able to apply the classical formulas

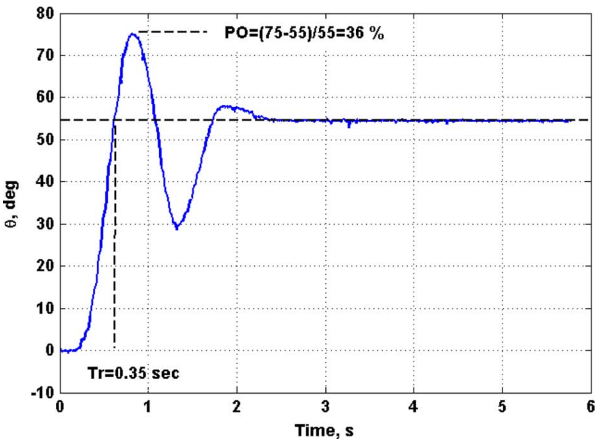

Fig. 10. Step response of closed-loop system.

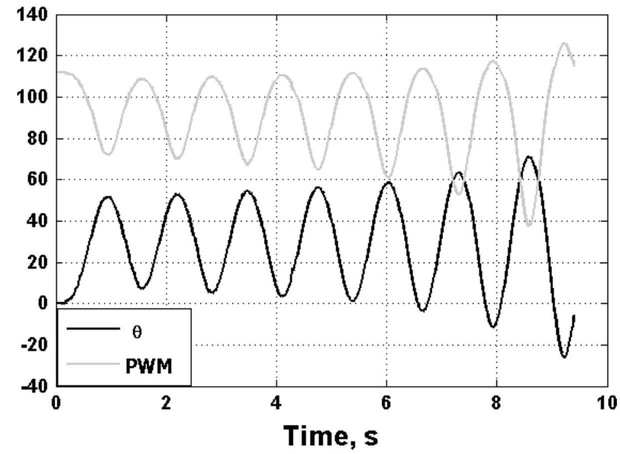

Fig. 11. Unstable response for $K_p = 3$.

presented in the course lectures to relate the plant parameters to system response parameters such as overshoot and rise-time

$$P.O. = \exp\left(-\zeta\pi/\sqrt{1-\zeta^2}\right) = 0.36$$
$$t_{\text{rise}} = \frac{1.8}{\omega_n} = 0.35. \tag{12}$$

In a more recent implementation, the length of the rod of the pendulum can be adjusted. When working with shorter lengths, the inertia is reduced, and the friction in the potentiometer becomes more dominant. The unit-feedback response of such pendulums has no overshoot. In such cases, students can use higher values of the feedback gain, e.g.,$K_p = 2$, leading to an underdamped response, and follow the same identification method. Alternatively, MATLAB's System Identification Toolbox pem command can be used to automatically estimate the parameters of the system. An example of its use is available online [21].

D. Model Fidelity

With the parameters fully identified, it is now possible to examine the validity of the model. To this end, the students are asked to apply the root locus design method and determine the behavior of the system (9)–(10) under different values of the feedback gain K_p. Using the root locus method, students predict that the system is stable under all values of K_p. However, when asked to run experiments for $K_p = 1, 2, 2.5, 3$, they realize that the response is stable for low values of the gain, and that the system loses its stability and the pendulum undergoes unstable oscillations, beyond a certain critical gain, as shown in Fig. 11. This experience leads to the fourth task, where the students are asked to examine their model and propose possible reasons for the observed discrepancy. Interestingly, the majority of the students (over 66%) provide inaccurate or superficial answers (discussed in Section IV). Upon submission of their responses, students are provided with a guided solution directing them to refine the model of the motor/propeller model by incorporating the dynamics of the motor current and propeller rotation. This results in the addition of a voltage-current equation

$$V = Ri + K_v\omega + L_{\text{ind}}\frac{di}{dt} \tag{13}$$

where R is the resistance of the motor coils, K_v is the back emf constant, and L_{ind} is the inductance of the motor coil. Similarly, the rotor dynamics is governed by

$$J_m\dot{\omega} = K_t i - C_Q\frac{\rho}{4\pi^2}D^5\omega^2 \tag{14}$$

where K_T is the motor torque constant, C_Q is the aerodynamic torque (drag) coefficient, ρ is the air density, and D is the diameter of the propeller [22]. Solving (14) for i and substituting in (13), it is easy to see that that V and ! are related through a second-order nonlinear differential equation for ω. Consequently, the input signal $\tilde{u}$ and the thrust force of the propeller are also subject to the dynamics of the associated poles. With this explanation, students are able to examine the effect of these two additional poles by assuming that they are approximately equal (critically damped pole pair) and reexamine the root locus of a fourth-order system

$$\frac{\Theta(s)}{W(s)} = \frac{KL}{mL^2s^2 + cs}\cdot\frac{1}{(1+T_{D1}s)(1+T_{D2}s)}. \tag{15}$$

A quick estimate of the effect of these poles can be made by assuming that they are close to each other and by examining a system with a critically damped pole-pair

$$\frac{\Theta(s)}{W(s)} = \frac{5.327}{s^2 + 3.649s}\cdot\frac{1}{(1+T_Ds)^2} \tag{16}$$

where the actual parameters of the transfer function (9) have been used.

The students are then asked to vary the value of the time constant T_D until the critical gain predicted from the root-locus agrees with the value obtained from experimentation $(K_p \approx 3)$. The corresponding plot is shown in Fig. 12. The resulting time constant is $T_D \approx 180$ ms, which matches tachometer measurements of the propeller [22]. This experience was well received, in particular by students who had struggled to come up with an explanation for the shortcomings of the second-order model. It also illustrates the use of the variational theory of learning in the design of the experiment. According to this theory, we learn through the experience of difference, rather than recognizing similarities. As Marton and coworkers state [16]: "What we believe is that variation enables learners to experience the

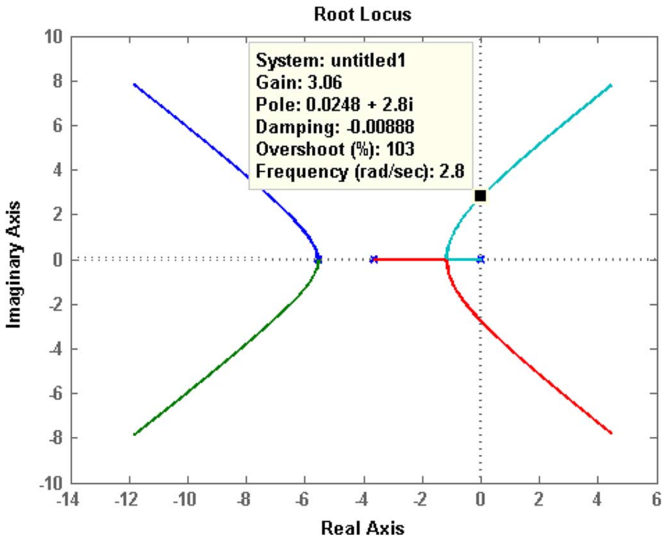

Fig. 12. Root locus of a fourth-order model incorporating motor-propeller dynamics.

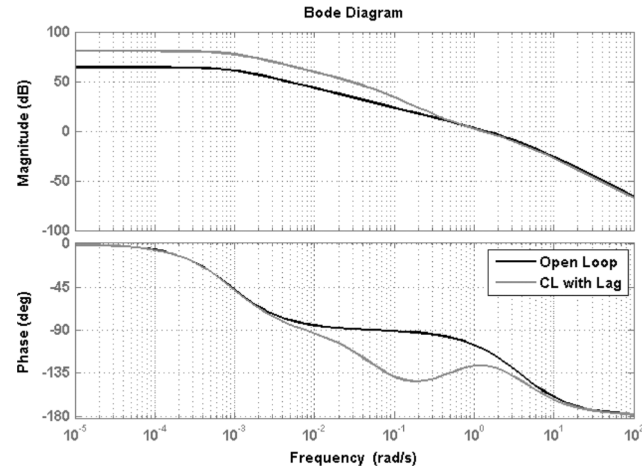

Fig. 13. Design of dynamic compensator (lag) in SISOTool.

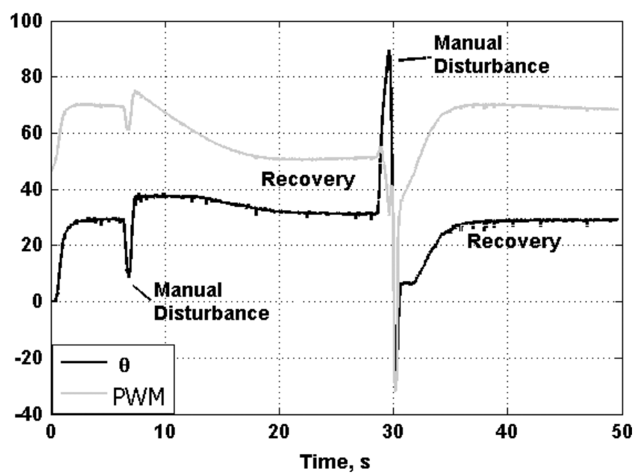

Fig. 14. Step response and disturbance rejection using phase lag compensation.

features that are critical for a particular learning as well as for the development of certain capabilities. In other words, these features must be experienced as dimensions of variations."

E. Design of Dynamic Compensator

The final assignment associated with the pendulum is to design a dynamic compensator. Typical performance specifications include a steady-state error of not more than 0.5 degrees and a setting time of not more than 3 s. Students are given the freedom of choosing a design method and compensator type, however most prefer using the frequency response techniques (Bode plots). It is worth noting that when the System Identification Toolbox's pem command is used, the extracted characteristic polynomial usually contains a small nonzero constant term (0.0033 in this case), which reflects the quality of the feedback linearization

$$\frac{\Theta(s)}{W(s)} = \frac{5.327}{s^2 + 3.649s + 0.0033}. \tag{17}$$

Following classroom examples, they import the plant's transfer function in MATLAB's SISOTool and use its Bode plot to examine gain crossover frequency and stability margins. The SISOTool allows them to graphically place the poles and zeros of their compensator and adjust the gain. An example of a phase lag (proportional + integral) compensator with a transfer function

$$C_{\text{lag}} = \frac{0.82575(s + 0.4771)}{s + 0.05936} \tag{18}$$

is shown in Fig. 13. Since a Real-Time Windows Target operates in the discrete domain, testing the performance of the compensator (18) requires a conversion of the compensator to a digital (discrete) transfer function using MATLAB's $c2d()$ function. The sampling time of the target board is determined by a function generator block inside the Simulink model. Since the target board uses a USB-to-serial driver, the actual data transfer speed and hence the limit of the sampling rate is that of the USB. Given the slow speed of the apparatus, we utilize a 10-ms update rate. The corresponding conversion command is $Clagd{=}c2d(Clag, 0.01, `zoh')$, resulting in

$$C_{\text{lagd}} = \frac{0.82575(z - 0.9952)}{z - 0.9994}. \tag{19}$$

Similarly, students perform a phase lead (proportional + derivative) controller design where they place the gain cross-over frequency around 20–30 rad/s. As expected, the resulting response is much faster, but with increased noise and larger overshoot. The response of the dynamically compensated plant with phase lag and lead controllers under multiple manually induced disturbances is shown in Figs. 14 and 15, respectively.

IV. Evaluation

During the 2008–2011 academic years, the project was offered to three cohorts with 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 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

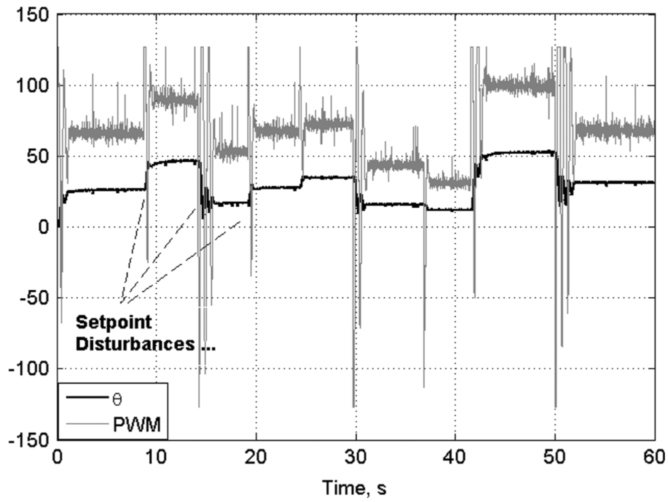

Fig. 15. Step response and disturbance rejection using phase lead compensation.

TABLE I
STUDENT FEEDBACK ON HOW WELL THE PROJECT ILLUSTRATES TECHNICAL CONCEPTS (PERCENTAGE; NUMBER OF RESPONSES IN PARENTHESES)

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

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. Table I shows the evaluation of technical content. As expected, the majority of the students found the system quite useful in illustrating the principles of control system design. 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 nonlinear systems and time delay. Interestingly, the highest gains were achieved in understanding of the relationship of stability and gain. When asked to comment on the discrepancy observed between the theory and experiment, 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. 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 h. Only 3.6% 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 h.

V. CONCLUSION

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 belief in the theory when confronted with an apparent contradiction with experimental observations. Evolution of the project has shown that presenting it 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 helping students whose major is not electrical engineering become 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 by students, and it can be completed independently over an average of 8 h. Parameter variation through modification of the configuration of the pendulum allows the instructor to individualize each kit.

REFERENCES

[1] Commission on Engineering Education, "New directions in laboratory instruction for engineering students," *J. Eng. Educ.*, vol. 58, no. 3, pp. 191–195, 1967.

[2] American Society of Engineering Education, Washington, DC, "The undergraduate engineering laboratory: Final report of the Quality of Engineering Education Project (QEEP)," 1986.

[3] E. W. Ernst, “The undergraduate engineering laboratory: 1983 Engineering Foundation Conferences, New England College, Henniker, New Hampshire, July 24–29, 1983 Engineering Foundation, 1983.
[4] ABET, Baltimore, MD, “Engineering criteria 2000,” 2002.
[5] M. Aburdene and M. El-Sharkawy, “Integrated engineering workstations in electrical engineering laboratories,” *IEEE Trans. Educ.*, vol. 32, no. 3, pp. 404–408, Aug. 1989.
[6] J. Kadlowec, P. Lockette, E. Constans, B. Sukumaran, and G. Cleary, “Visual beams: Tools for statics and solid mechanics,” in *Proc. 32nd ASEE/IEEE Frontiers Educ. Conf.*, Boston, MA, Nov. 2002, pp. T4D-7–T4D-10.
[7] P. Horàcek, “Laboratory experiments for control theory courses: A survey,” *Annu. Rev. Control*, vol. 24, pp. 151–162, 2000.
[8] R. V. de Molengraft, R. Steinbuch, and B. Kraker, “Integrating experimentation into control courses,” *IEEE Control Syst.*, vol. 25, no. 1, pp. 40–44, Feb. 2005.
[9] R. M. Felder, “Reaching the second tier-learning and teaching styles in college science education,” *J. Coll. Sci. Teaching*, vol. 23, no. 5, pp. 286–290, 1993.
[10] R. Dunn, “Learning styles and its relation to exceptionality at both ends of the spectrum,” *Exceptional Children*, vol. 49, pp. 496–506, 1983.
[11] S. Papert, *Mindstorms: Children, Computers, and Powerful Ideas*. New York: Basic Books, 1980.
[12] I. Harel and S. Papert, *Constructionism*. Norwood, NJ: Ablex, 1991.
[13] J. Sarik and I. Kymissis, “Lab kits using the Arduino prototyping platform,” in *Proc. IEEE FIE*, Oct. 2010, pp. T3C-1–T3C-5.
[14] P. J. Gawthrop and E. McGookin, “A Lego-based control experiment,” *IEEE Control Syst.*, vol. 24, no. 5, pp. 43–56, Oct. 2004.
[15] F. Marton and A. S. Booth, *Learning and Awareness*. Mahwah, NJ: Erlbaum, 1997.
[16] F. Marton and A. Tsui, *Classroom Discourse and the Space of Learning*. Mahwah, NJ: Erlbaum, 2004.
[17] I. Halloun and D. Hestenes, “Modeling instruction in mechanics,” *Amer. J. Phys.*, vol. 55, pp. 455–462, 1987.
[18] R. Hake, “Promoting student crossover to the newtonian world,” *Amer. J. Phys.*, vol. 55, pp. 878–884, 1987.
[19] D. Sokoloff, R. K. Thornton, and P. Laws, *Real Time Physics Module 1: Mechanics*. New York: Wiley, 1998.
[20] R. Thornton, “Tools for scientific thinking: Microcomputer-based laboratories for teaching physics,” *Phys. Educ.*, vol. 22, pp. 230–238, 1987.
[21] E. T. Enikov, “Aeropendulum project,” 2011 [Online]. Available: http://aeropendulum.arizona.edu/
[22] V. Glowacka, “Modeling of nonlinearities in a propeller-driven pendulum,” Master’s thesis, University of Arizona, Tucson, AZ, 2009.

Eniko T. Enikov (M’10) received the M.S. degree from the Technical University of Budapest, Budapest, Hungary, in 1993, and the Ph.D. degree from the University of Illinois at Chicago in 1998, both in mechanical engineering.

As a Postdoctoral Associate with the University of Minnesota, Minneapolis, he has worked on several projects in the area of microassembly, capacitive force sensing. Currently, he is an Associate Professor with the Aerospace and Mechanical Engineering Department, University of Arizona, Tucson, where he established the Advanced Micro- and Nanosystems Laboratory. His research is focused on the design and fabrication of microelectromechanical systems (MEMS) as well as developing theoretical models of multifunctional materials used in MEMS. His group at the University of Arizona has an ongoing research program on tactile displays, electrostatic micro-grippers for assembly of MEMS, and nanoassembly of macromolecules using electrostatic fields, as well as development of MEMS-compatible wireless sensing platforms with biomedical applications.

Dr. Enikov is a member of the professional societies of ASME and ASEE.

Giampiero Campa (M’00) received the Laurea degree in electrical engineering and Ph.D. degree in robotics and automation from the University of Pisa, Pisa, Italy, in 1996 and 2000, respectively.

He has also worked with the Industrial Control Centre, Strathclyde University, Glasgow, U.K., in 1995, and with the Department of Aerospace Engineering, Georgia Institute of Technology, Atlanta, in 1999. From 2000 to 2008, he has served as faculty with the Flight Control Group, Department of Aerospace Engineering, West Virginia University (WVU), Morgantown. His research at WVU involved system identification, adaptive and nonlinear control, fault-tolerant systems, machine vision, and sensor fusion, especially applied to unmanned aerial vehicles (UAVs). Since January 2009, he has worked with MathWorks, Inc., as the Technical Evangelist for the US West Coast area.