2021 ASEE ANNUAL CONFERENCE
Virtual Meeting | July 26–29, 2021 | Pacific Daylight Time
Paper ID #33645

Low-cost Open-architecture Experimental Platform for Dynamic Systems and Feedback Control

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Abstract

Conventional experimental systems used in the dynamic systems and controls engineering sub-discipline are expensive and non-portable. Further, the high cost can limit the number of experimental apparatuses available and reduce the time in which each student can interface with the hardware. Low-cost learning platforms offer an alternative method to deliver similar learning outcomes afforded by conventional platforms at an affordable cost in a portable package, greatly improving accessibility for all students. In this paper, the design, theory, functionality, and educational merit of a low-cost, portable 2nd-order dynamical pendulum system are discussed.

Introduction

Traditional dynamic systems and controls learning platforms are costly, non-portable, and require substantial laboratory space[1,2]. Due to the limited number of systems available, these traditional systems must be shared amongst groups of students, resulting in reduced individual hands-on time. Fortunately, recent advances in microcontroller technology as well as data acquisition capabilities have allowed educators to adopt low-cost affordable systems that can replace traditional dynamic systems while preserving the key learning outcomes at an affordable price[3,8]. Still, many of these solutions require proprietary hardware and/or proprietary software to perform the required data acquisition[9,10]. Additionally, recent research has been conducted with the vision to convert engineering classes to online classes as alternatives to traditional in-person classes[6,7]. Due to the nature of the abrupt change resulting from the COVID-19 pandemic, many students have been left dissatisfied with the quality of their education and have requested different approaches to the current online learning routine[5,11]. Laboratory activities have significantly been affected due to the lack of hands-on experience. Research suggests that students with applied knowledge have an advantage over student with only theoretical knowledge within the industry, and the preferred means to gain applied knowledge is from laboratory classes within the curriculum[4]. This paper presents the design and educational merit of a low-cost, portable, multidisciplinary pendulum platform that enables students to conduct experiments remotely. This system aims to address the high-cost, lack of mobility, lack of accessibility and large space accommodations that traditional dynamic systems and controls learning platforms present.

The learning outcomes are similar to their traditional high-cost counterparts and include: system identification, modeling, simulation, s-domain analysis, frequency-domain analysis, and feedback control principles. Further setting this low-cost experimental system apart from others is the open architecture. The hardware is comprised of common off-the-shelf components and 3D printed parts for which the design files are publicly available (see Concluding Remarks). The total cost for this kit is less than $100 USD retail. Data acquisition and hardware interfacing are conducted through industry-standard computational packages like MATLAB/Simulink, LabView, or Arduino IDE and the system allows for sufficiently fast sample rates (350Hz - 450Hz) with no proprietary software or plugins. This paper describes the design and educational outcomes of a sub-$100 take-home 2nd-order mechatronics kit designed to match the learning objectives afforded by a traditional laboratory experiment.

Dynamic Systems

Experimental platforms such as Educational Control Products (ECP's) torsional[1] and rectilinear plants[2] (Fig. 1) are examples of traditional dynamics and controls systems found in most institutions. The purpose of these systems is to reinforce concepts studied in common core engineering courses such as Dynamic Systems and Feedback Control of Mechanical Systems. Typical concepts reinforced by these traditional laboratory systems include: dynamic system modeling, 1st- and 2nd-order system behavior, system identification, and control system design.

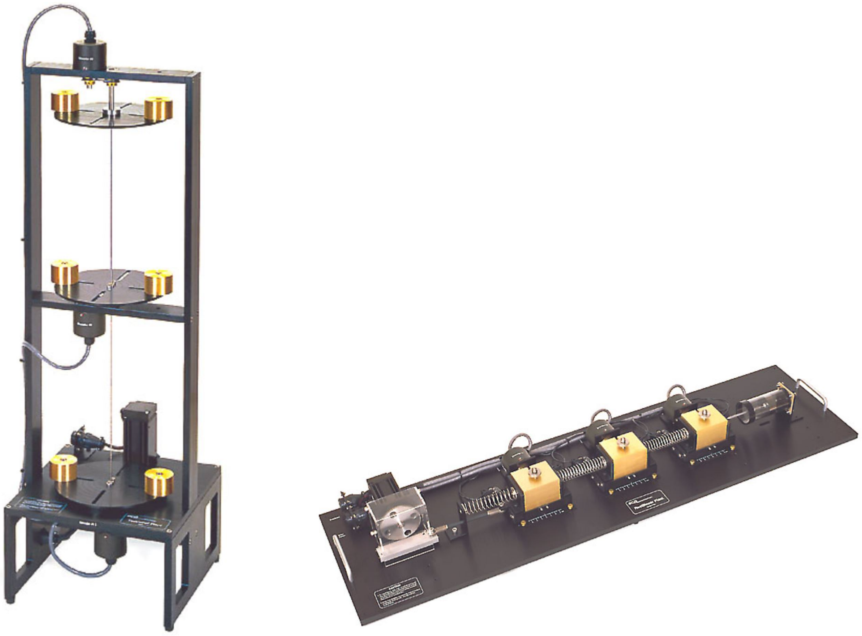


Figure 1: Educational Control Products: Torsional Plant (Left), Rectilinear Plant (Right)

Characteristics of these traditional plants make them a compelling choice for educational learning. These systems are designed to be student-proof. They incorporate many safety features such as current and voltage limiters and physical limit switches that reduce the possibility of damage by inexperienced students. Further, they are constructed from high-quality machined parts and are designed for long-term use. Importantly, these turn-key solutions usually offer high quality analog-to-digital converters and hardware interfaces that allow for high sample rates ($f_s >$ 1 kHz), which is necessary for capturing fast-moving mechanical systems.

The drawbacks of these traditional systems all generally stem from their large size and high cost. For instance, with a total footprint ranging from $5 - 8ft^2$ the total number of systems that can fit in a given lab space is limited. Further, the cost is usually prohibitively high, one turnkey system can exceed $20,000, and university laboratories cannot generally afford to purchase enough systems to allow each student a dedicated unit. Finally, while some turnkey solutions offer software plugins (at an additional cost) to allow the use of industry standard software, many require the use of proprietary software for data acquisition, which may not translate well to industry applications.

Low-cost take-home kits are strong alternatives to their conventional counterparts due to their minimal cost, small footprint, and portability. The 2nd-order Pendulum platform (Fig. 4) is constructed from strategically specified off-the-shelf components and costs less than $100. It is designed and built to remedy the several drawbacks associated with the traditional platforms and retains all of the key learning objectives.

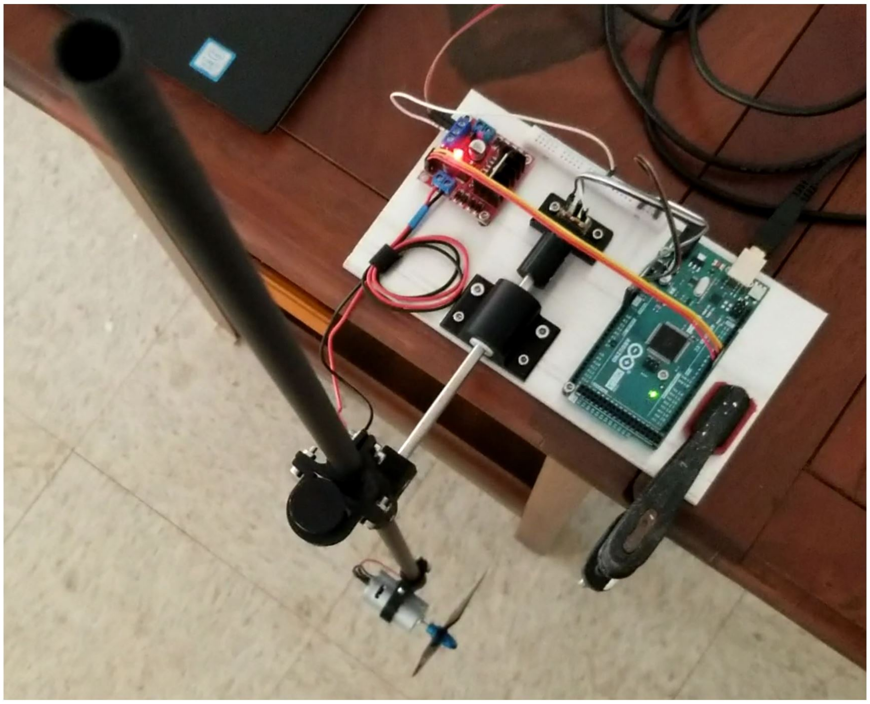


Figure 2: Low-Cost 2nd-Order Pendulum System

The 2nd-order pendulum system discussed in this paper is small enough for students to conduct experiments at home. The system can be assembled from widely available components and public available 3D printable parts for under $100. This makes replacing broken components effortless and inexpensive. The design intent is to allow every student access to their own system, which increases individual interaction time and presumably improves comprehension of core concepts.

Low-Cost Experimental Pendulum System

The pendulum platform (Figure 4) is based on the simple pendulum which demonstrates 2nd-order dynamic behavior studied in all undergraduate dynamics courses. The pendulum described in this paper is actuated and can measure angular displacement data for subsequent analysis. A DC motor and propeller assembly controlled by a dedicated motor controller can produce arbitrary user-defined input profiles. Additionally, a counterweight is incorporated which allows adjustability of the plant dynamics.

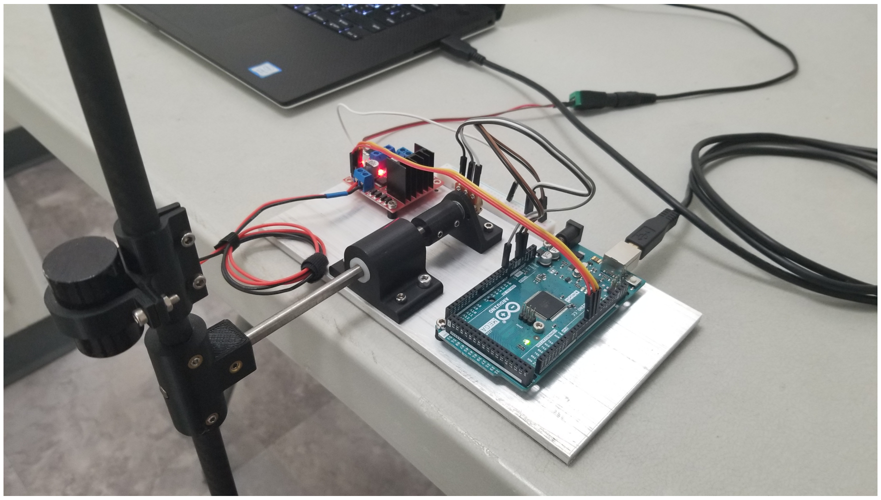


Figure 3: Low-Cost System Hardware Interface

This plant consists of a lightweight carbon fiber swing arm, a motor and propeller assembly, an Arduino MEGA 2560, an L298N DC motor driver, a rotary potentiometer, a flat mounting plate, and a few 3D printed parts (Figure 5) for which design files are openly available. The carbon fiber rod is connected via a “T-joint” which is connected to the primary rotary shaft. The shaft is coupled directly to a potentiometer’s shaft. Position data is obtained using the potentiometers’ 10-bit analog output. These parts are off-the-shelf items and commonly available for retail purchase. This platform is designed to be clamped to any surface, making it usable on any tabletop.

Dynamic Behavior and Modeling

A simple point-mass model is used for the free body diagram analysis (Figure 6). The masses accounted for in the dynamics are the counterweight (m_1) and the motor and propeller assembly (m_2). Note that the mass of the carbon fiber rods are not accounted for in this analysis. The forces that are accounted for in the free body diagram are the weights for each mass (W_1 and W_2), propeller thrust (F_t), and drag force for the motor and propeller assembly (F_d).

Figure 4: Low-Cost System: Side View (Left), Front View (Right)

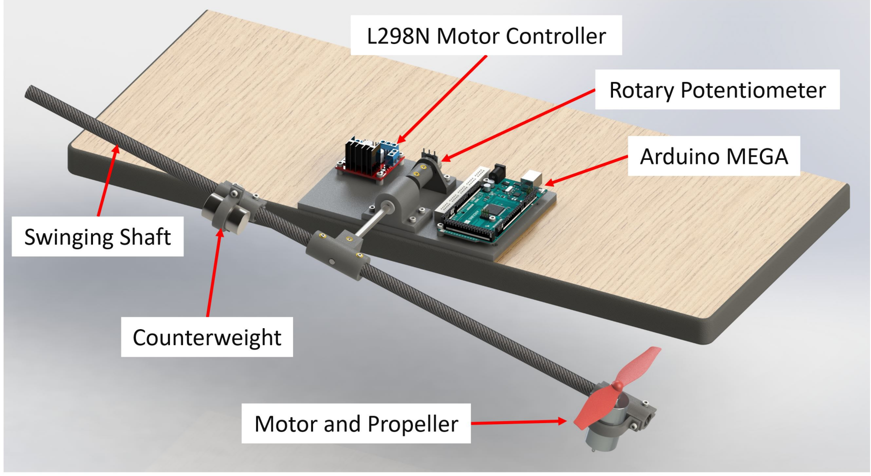


Figure 5: Solidworks CAD rendering of the Pendulum plant.

Modeling this system is possible using Newtonian Mechanics for rotational dynamics. The sum of the torques (ΣT_o) about the point of rotation is found by using the forces in Figure 6. The product of the rotational inertia (J) and the rotational acceleration (α) is equal to the sum of the torques (ΣT_o):

$$\Sigma\, T_o = J\alpha \tag{1}$$

Taking Newton's Law, the governing equation can be derived. Although there are multiple forces contributing to energy dissipation (friction, aerodynamic drag), a single linear drag force F_d is used in this model.

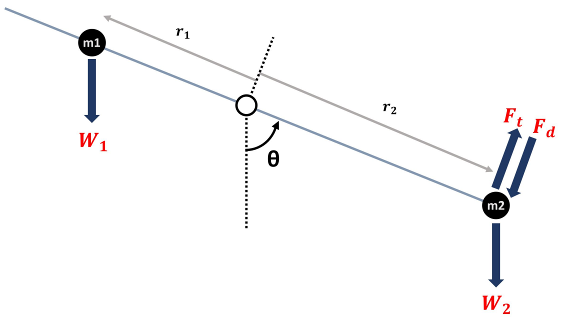


Figure 6: Free Body Diagram of the Pendulum Plant.

$$W_1 r_1 \sin(\theta) - W_2 r_2 \sin(\theta) + F_t r_2 - F_d r_2 = J\alpha \tag{2a}$$

$$m_1 g r_1 \sin(\theta) - m_2 g r_2 \sin(\theta) + F_t r_2 - F_d r_2 = J\alpha \tag{2b}$$

Mass moment of inertia is given by:

$$J = J_1 + J_2 + J_{rod} \tag{3}$$

In this development, the inertial effects of the carbon fiber rods are considered negligible ($J_{rod} = 0$) and the motor and propeller assembly as well as the counterweight assembly are approximated as point masses. The moment of inertia that is used in this analysis is simplified with these assumptions.

$$J = m_1 r_1^2 + m_2 r_2^2 \tag{4}$$

Employing Newton's third law and using the free body diagram leads to the system's ordinary differential equation (ODE).

$$\begin{aligned} m_1 g r_1 \sin(\theta) - m_2 g r_2 \sin(\theta) + F_t r_2 - b\dot{\theta} r_2 &= J\ddot{\theta} \\ J\ddot{\theta} - m_1 g r_1 \sin(\theta) + m_2 g r_2 \sin(\theta) + b\dot{\theta} r_2 &= F_t r_2 \\ (m_1 \frac{r_1^2}{r_2} + m_2 r_2)\ddot{\theta} - m_1 g \frac{r_1}{r_2} \sin(\theta) + m_2 g \sin(\theta) + b\dot{\theta} &= F_t \\ (m_1 \frac{r_1^2}{r_2} + m_2 r_2)\ddot{\theta} + (b)\dot{\theta} + (m_2 g - m_1 g \frac{r_1}{r_2}) \sin(\theta) &= F_t \end{aligned}$$

A second-degree, non-linear, non-homogeneous ODE is found as the governing equation.

$$A\,\ddot{\theta} + B\,\dot{\theta} + C\sin(\theta) = F_t \tag{5}$$

where the coefficients of the ODE in (5) are:

$$A = m_1 \frac{r_1^2}{r_2} + m_2 r_2 \tag{6a}$$

$$B = b \tag{6b}$$

$$C = m_2 g - m_1 g \frac{r_1}{r_2} \tag{6c}$$

Small angle approximation can be used to ensure that equation (5) is linear.

$$\sin(\theta) \approx \theta \tag{7}$$

The assumptions and analysis lead to the Linear and Time-Invariant (LTI) ODE.

$$A\,\ddot{\theta} + B\,\dot{\theta} + C\,\theta = F_t \tag{8}$$

A Simulink model (Figure 7) can be constructed to solve for the theoretical output of the system. This is achievable by strategically manipulating equation (5) and (7).

$$\ddot{\theta} = \frac{1}{A}(F_t - B\dot{\theta} - C\sin(\theta)) \tag{9}$$

$$\ddot{\theta} = \frac{1}{A}(F_t - B\dot{\theta} - C\theta) \tag{10}$$

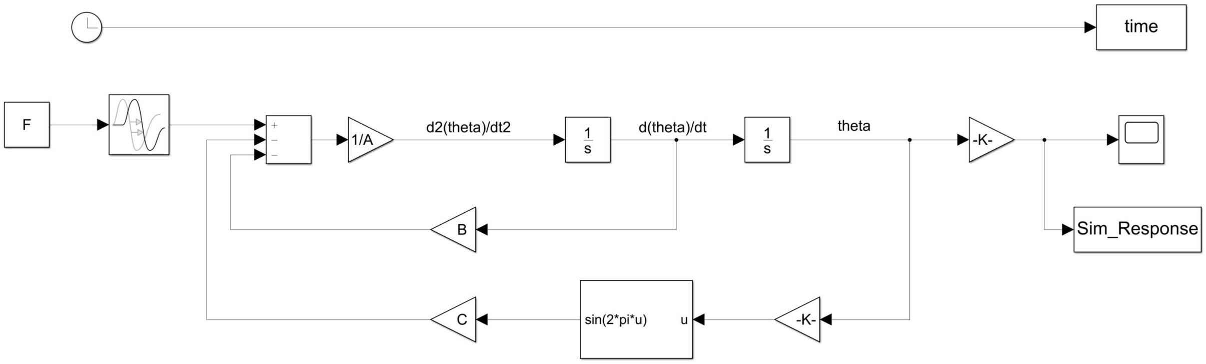


Figure 7: Example of Simulink Modeling for the dynamics of the plant.

It was determined that the system can be modeled as an LTI system. Therefore, finding the transfer function can be obtained by simply applying the Laplace operator.

$$\begin{aligned} \mathscr{L}(A\ddot{\theta} + B\dot{\theta} + C\theta) &= \mathscr{L}(F_t) \\ As^2\Theta + Bs\Theta + C\Theta &= \Gamma \\ \Theta(As^2 + Bs + C) &= \Gamma \end{aligned} \tag{11}$$

The transfer function for this system is found.

$$\frac{\Theta}{\Gamma} = \frac{1}{A\,s^2 + B\,s + C} \tag{12}$$

Second-order system transfer functions are typically represented with their damping ratio (ζ) and natural frequency (ω_n). The transfer function takes a form with ζ and ω_n included.

$$H = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n\,s + \omega_n^2} \tag{13}$$

If the transfer function of this system is forced to take the form of a typical second-order system, the transfer function for the Pendulum takes a slightly different form.

$$\frac{\Theta}{\Gamma} = C^{-1}\frac{\omega_n^2}{s^2 + 2\zeta\omega_n\,s + \omega_n^2} \tag{14}$$

where ζ and ω_n in (14) take the following values:

$$\zeta = \frac{B}{2}\sqrt{\frac{1}{AC}} = \frac{b}{2}\sqrt{\frac{r_2}{(m_1r_1^2 + m_2r_2^2)(m_2r_2 - m_1r_1)g}} \tag{15}$$

$$\omega_n = \sqrt{\frac{C}{A}} = \sqrt{\frac{(m_2r_2 - m_1r_1)g}{m_1r_1^2 + m_2r_2^2}} \tag{16}$$

Several lessons can be developed from the modeling of this plant. The final transfer function (Equation 14) can be used to construct lessons in system identification, modeling, simulation, and s-domain analysis.

Hardware Interfacing and Data Acquisition

These low-cost open-source platforms provide unique opportunities for programming using standard software packages. As previously stated, these platforms are programmable via MATLAB, Simulink, LabView, or Arduino. Instead of students being handed pre-made software, students can create their own Simulink models (.slx) and LabView virtual instruments (.vi) to perform various analyses. This paper focuses on Simulink and LabView since they are frequently used in industry.

Through Simulink's *Simulink Support Package for Arduino Hardware*, Simulink models can be ran externally on the Arduino MEGA. Blocks from this package allow a Simulink model to access the Arduino's digital and analog capabilities. Processes such as sending a duty cycle signal to the H-bridge is possible. Figures 8 and 9 present the experimental and simulated results from a step response. The simulated data were produced by computing the variables in equation 8 using a combination of physical measurements and parameter estimation techniques, which is a common practice in dynamic system modeling. A linear model sufficient for academic purposes is shown in Fig. 8, while a more accurate model based on the nonlinear system is shown in Fig. 9.

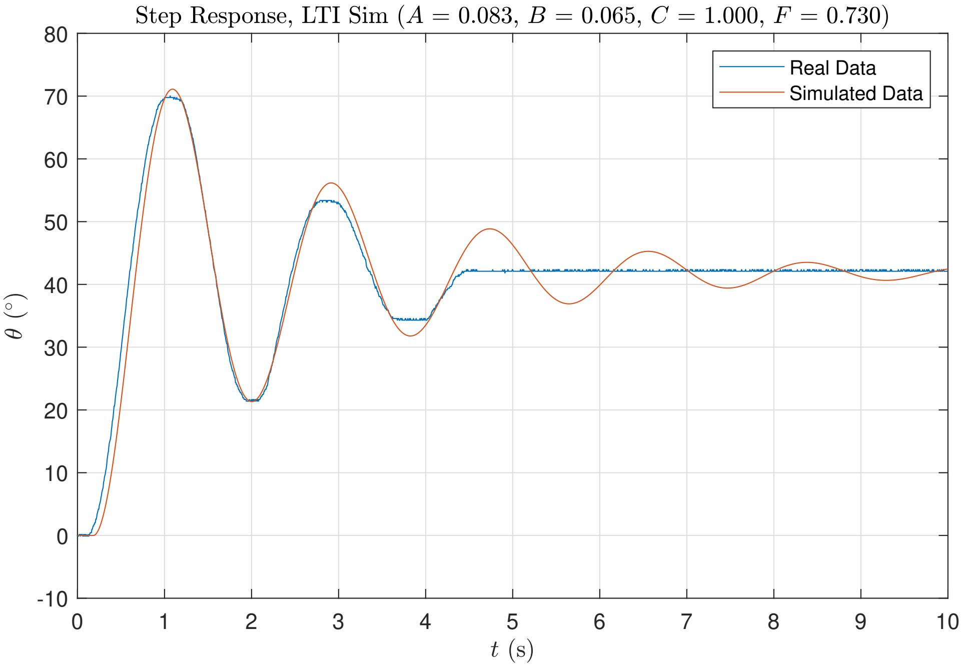


Figure 8: Experimental vs Simulated Data (Linear Model)

In both cases, the stiffness term corresponding to the damped frequency is more easily identified than the highly nonlinear damping term corresponding to the rate of decay. This is likely due to the nature of the friction in the potentiometer, which is left unmodeled in this paper for the sake of simplicity. A more complex model would likely account for this additional friction, however the scope of this endeavor may be beyond that of an undergraduate systems course. Nonetheless, with a transfer function representation of the experimental system, students are consequently able to do control design activities in simulation, and subsequently verify their designs on the real system, which is common practice in industry and academia.

Figure 10 shows the step response of a particular pendulum setup. The angle of the shaft (i.e., the potentiometer measurement) was captured through an "Analog Read" function. Three different data sets are superimposed to demonstrate the system's repeatability.

Figure 11 shows the results from an experimental run of a PID Controller implementation. PID

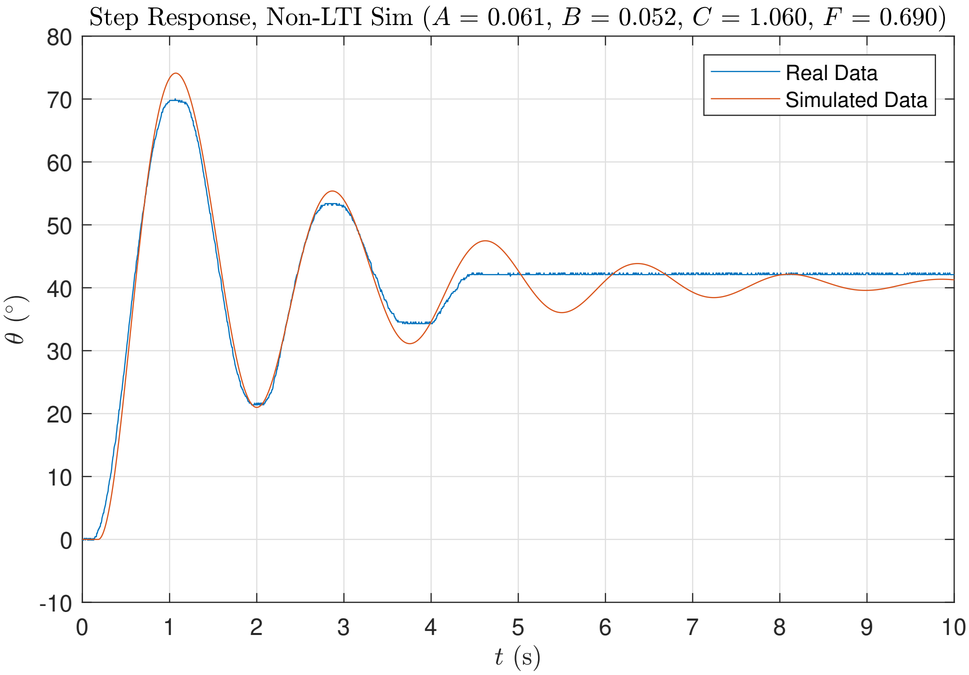


Figure 9: Experimental vs Simulated Data (Non-Linear Model)

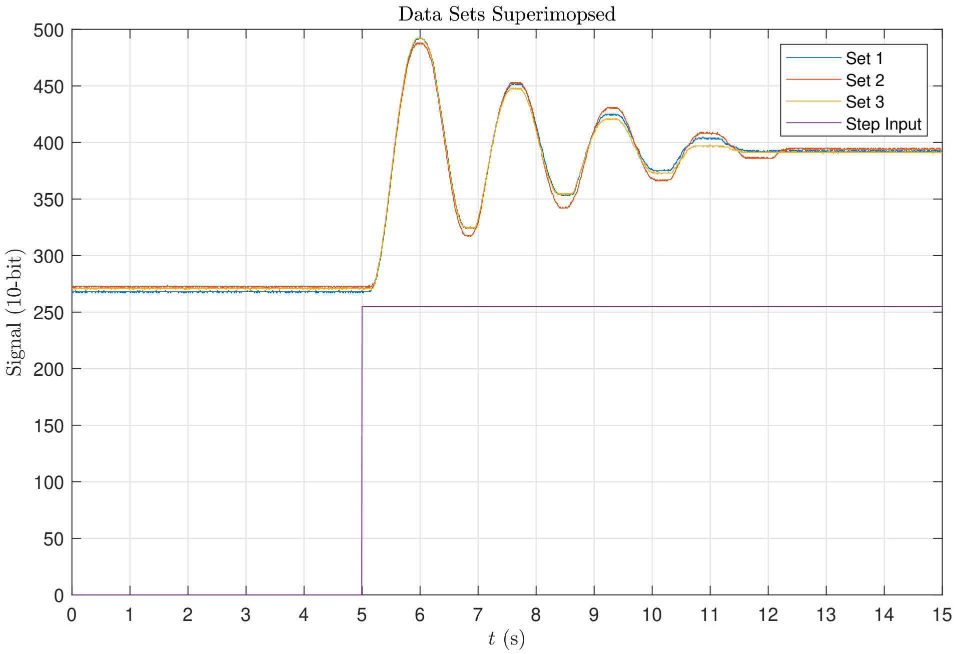


Figure 10: Shaft orientation data obtained from Simulink when subjected to a step input.

parameters were tuned and satisfactory performance was obtained. A potentiometer was used to control the reference point of the pendulum (blue curves).

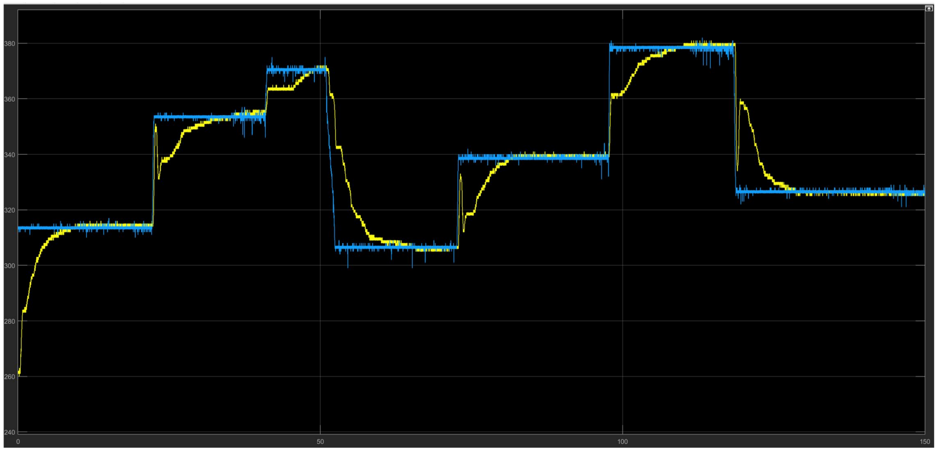
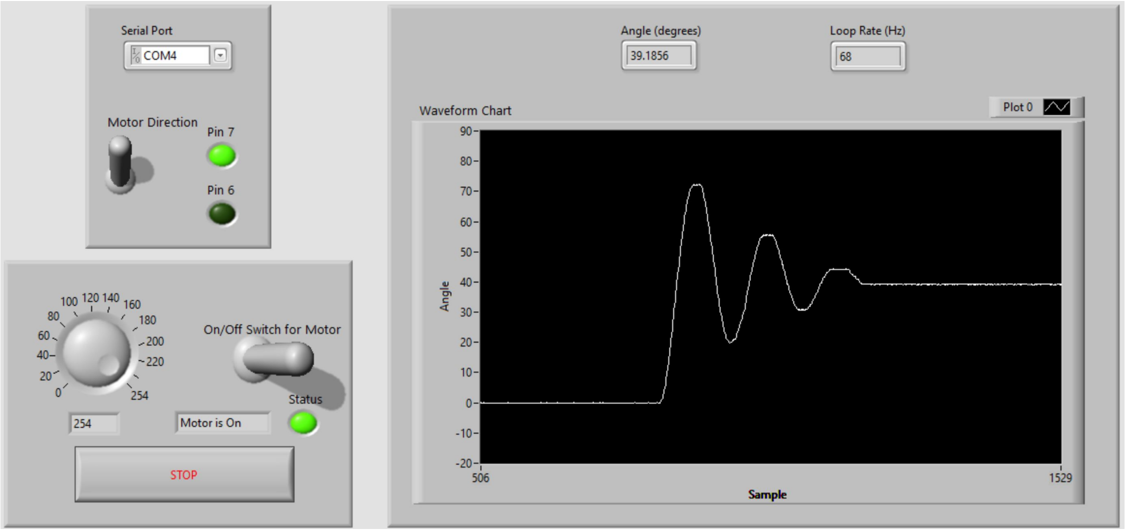


Figure 11: A control implementation for the Pendulum plant using Simulink.

LabView is another industry-standard software package that can be used to program the system. Programming the Arduino MEGA is possible through LabView's *LINX Maker Hub* package. Like the Simulink Arduino package, the Arduino's analog and digital functions are unlocked using this software package. The advantage that LabView has over Simulink is that the "front panel" offers superior customization. Buttons, LEDs, displays, dials, and much more can be utilized to streamline the process of controller tuning or input response testing.

Figure 12 shows the front panel of an experimental input response setup on the pendulum platform. Notice how the dial and motor switches enable real-time testing.


Serial Port: COM4

Angle (degrees): 39.1856

Loop Rate (Hz): 68

254

Motor is On

Figure 12: Real-time results from an input response implementation for the Pendulum plant using LabView.

Figure 13 is a screen shot of real-time PID tuning. LabView's *Control & Simulation* package facilitates the process of creating a robust PID controller for the system. Notice the numeric controls for each parameter of the PID controller. The reference of the shaft can also be varied in real-time.

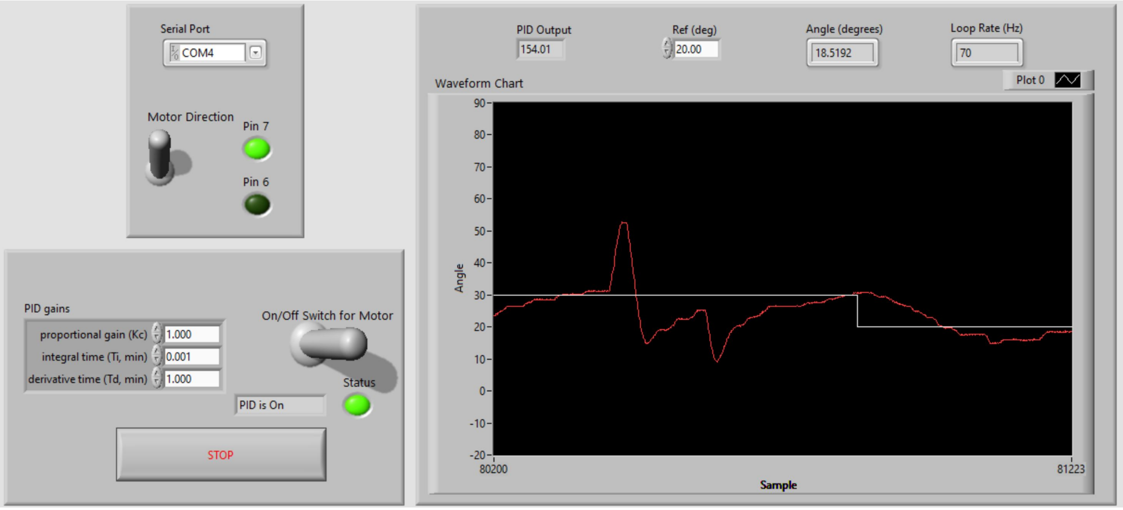

Serial Port: COM4
PID Output: 154.01
Ref (deg): 20.00
Angle (degrees): 18.5192
Loop Rate (Hz): 70
proportional gain (Kc): 1.000
integral time (Ti, min): 0.001
derivative time (Td, min): 1.000
Status: PID is On

Figure 13: A control implementation for the Pendulum plant using LabView.

Both MATLAB/Simulink and LabView software enable the students to learn valuable industry skills. PID tuning and input analysis are easily achievable using this software avenue.

Low-Cost Dynamic System vs. Traditional Experimental System

Low-cost dynamic system described in this paper is capable of delivering a similar educational experience when compared to a traditional experimental system. Both plants allow for modifications to the plant mechanics and both systems allow students to design and implement custom controllers. Also, both systems are compatible with industry standard software such as Simulink and LabView by using free plugins.

A major drawback of the traditional system is the footprint; the low-cost system requires a fraction of the space and it's light and portable enough for students to transport between home and campus. While some have criticized the use of Arduino as a valid interface for academically rigorous experiments, the authors have explored the limits of the low-cost board and determined that sufficiently fast sample rates can be achieved (350Hz - 450Hz) without the need for more powerful hardware. Careful design of the low-cost plant's time constant allows these sample rates to be more than adequate for capturing all of the inherent dynamics. Additionally, given the low cost and portability, the low-cost system also affords a higher degree of accessibility for all students, consequently improving the remote learning experience. Finally, the cost of the Low-Cost Plant is under $100 while an ECP unit costs over $20,000 which makes it possible for each student to interface with their own system, rather than sharing one system with dozens of other students.

Despite the several benefits of adopting the low-cost option, there are some potential drawbacks. It can be argued that teamwork is an integral part of any lab experience, and offering each student their own system will deny students this collaborative environment. Additionally, the traditional systems generally are capable of sample rates an order of magnitude fast than the low-cost option (5,000Hz+). However, as the authors have demonstrated, it is straightforward to strategically produce a ”slower” system through intentional design, which places a much lower requirement on sampling. Finally, as a build-your-own kit of sorts, the low-cost option does introduce the possibility of user error upon construction of the system, which could lead to problems when running experiments. This is likely the biggest source of variation between results, so it is important to provide supplemental materials such as detailed introductory videos and setup manuals to help students get started.

Concluding Remarks

This paper has described the design and development of a low-cost dynamic system apparatus that can be an effective alternative to traditional expensive large-scale experimental solutions. Simulation and data acquisition are performed using industry-standard software. Measured outputs from this system align remarkably well with the theoretical model, based on a traditional 2nd-order system. Further work includes improving the robustness of the system, as well as reducing costs further through adopting generic interface boards and exploring bulk discounts for large engineering departments. The authors intend to deploy this low-cost platform in a Control Systems course and solicit student feedback to be featured in a subsequent study.

A full Bill of Materials (BOM) along with all required 3D print STL files can be found here: https://github.com/TheMachine951/Pendulum

References

[1] Educational control products model 210: Rectilinear plant, . URL `http://www.ecpsystems.com/controlsrecplant.htm`.

[2] Educational control products model 205: Torsional plant, . URL `http://www.ecpsystems.com/controlstorplant.htm`.

[3] K. Asato, K. Asato, T. Nagado, , and S. Tamaki. Development of low cost educational material for learning fundamentals of mechatronics. In *IEEE Xplore*, https://ieeexplore.ieee.org/abstract/document/7439526, Nov 2015.

[4] M. Gunasekaran and R. Potluri. Low-cost undergraduate control systems experiments using microcontroller-based control of a dc motor. In *IEEE Transactions on Education*, volume 55, pages 508–516, Nov 2012.

[5] T. Hattingh, W. van Niekerk, H. Marais, and Y. Geldenhuys. Engineering student experiences of a remotely accessed, online learning environment. In *IEEE Xplore*, https://ieeexplore.ieee.org/document/9293652, Nov 2020.

[6] P. N. Kawamoto, Y. Fuwa, H. Kunimune, E. Iwama, and J. Tanaka. Work in progress: Sharing learning resources in the development of an online engineering presentations course. In *IEEE Xplore*, https://ieeexplore.ieee.org/document/4117231, Oct 2006.

[7] C. C. Ngo and F. C. Lai. An online thermodynamics courseware. In *Computer Applications in Engineering Education*, volume 11, pages 75–82, 2003.

[8] A. Soriano, L. Marín, M. Vallés, A. Valera, and P. Albertos. Low cost platform for automatic control education based on open hardware. In *IFAC Proceedings*, volume 47, pages 9044–9050, 2014.

[9] A. Steinhauser. Low-cost carry-home mobile platforms for project-based evaluation of control theory. In *IFAC-PapersOnLine*, volume 50, pages 9138–9143, July 2017.

[10] B. Taylor, P. Eastwood, and B. Ll. Jones. Development of a low-cost, portable hardware platform for teaching control and systems theory. In *IFAC Proceedings*, volume 46, pages 208–213, Jan 2013.

[11] Y. Zhe, S. Binbin, L. Chunrun, B. Minghao, and W. Yutian. Problems and suggestions of online learning for chemical engineering majors in colleges and universities. In *IEEE Xplore*, https://ieeexplore.ieee.org/document/9262494, Jun 2020.