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# BOARD # 270: Multiple Representations of Learning in Dynamics and Control: Exploring the Synergy of Low-Cost Portable Lab Equipment, Virtual Labs, and Artificial Intelligence within Student Learning Activities; NSF IUSE Level 2, Award No: 2336998

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# Multiple Representations of Learning in Dynamics and Control: Exploring the Synergy of Low-Cost Portable Lab Equipment, Virtual Labs, and Artificial Intelligence within Student Learning Activities

**NSF IUSE Level II - 2336998**

**1. Problem Statement.** The challenge of learning abstract, theoretical concepts and connecting them to real-world behavior can be significant for engineering students, particularly in the highly mathematical context of dynamics, vibrations, and control theory concepts [1-3]. Also, students struggle with visualizing and interpreting the fundamentals of vibrations and control theory [4,5]. Hands-on experiences are especially crucial for engineering students to help them bridge the gap between theory and its application [6]. Hands-on equipment utilized in vibrations and control labs allows students to engage with physical systems, validate theoretical concepts, and design and implement control systems. However, most mechanical engineering courses, such as vibrations and control theory, are 3-credit lecture-only courses without integrated laboratories, unlike many electrical, computer, and mechatronics programs [7]. Moreover, since the pandemic, digital learning tools have become necessary complements, not just accessories, to support student engagement and learning. They offer advantages to increase student learning that traditional laboratory environments cannot, including increased accessibility for students with mobility impairments. Although some open-source virtual labs are available for K-12 and science courses [8-10], there are a very limited number of virtual labs for undergraduate engineering courses including vibrations and control theory courses [11,12]. Finally, research shows that AI applications in education can be instrumental in offering personalized learning experiences [13-15]. Therefore, the implementation of AI technologies in learning activities can help identify where students struggle the most and provide valuable feedback and resources.

**2. Proposed Study and Research Methodology.** This study builds upon our NSF Level 1 proposal, which focused on developing learning activities using low-cost, portable, 3D-printed lab equipment for undergraduate engineering courses. Here we explore the effectiveness of combining these tools with virtual simulations and AI-powered feedback to create comprehensive dynamics and control learning packages suitable for dynamics, vibrations, and control-related courses offered in mechanical, mechatronics, and electrical and computer engineering programs at multiple institutions. We are exploring the following research questions: **1.** To what degree can learning packages enhance student learning capabilities around dynamics and controls within the context of carefully designed AI-assisted learning experiences using hands-on equipment and virtual simulations? **2.** Why do potential users choose to use one or more parts of the dynamics and control learning package? **3.** Which element or combinations of elements in the dynamics and controls learning package are most beneficial for its users?

**3. Results.** Since the beginning of the project (April 2024), we implemented our previously designed pendulum and its learning activity as a homework assignment in a System Dynamics and Control Theory course taught by the principal investigator. Additionally, we designed and developed a new control lab equipment which has been implemented in the Embedded Digital Control course taught by the other principal investigator at Kennesaw State University and with a faculty in the Introduction to Robotics Lab at the University of Muchigan-Dearborn.

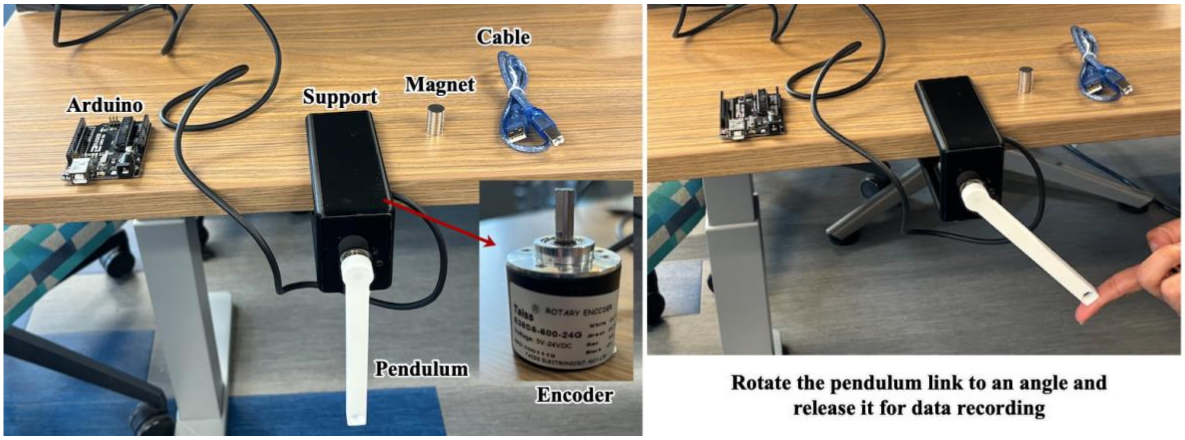


Figure 1. SDOF pendulum kit

**3.1 SDOF Pendulum Kit.** We designed a low-cost, portable pendulum kit consisting of a Taiss encoder ($19), Arduino ($20), and a small magnet serving as the tip load as shown in Figure 1. This simple design provides students with a tangible way to understand fundamental concepts of motion by observing and comparing experimental, theoretical, and simulated responses. The pendulum kit allows students to observe and manipulate parameters like damping, reinforcing their comprehension of key concepts such as principal modes and natural frequency.

**Implementation of Pendulum in System Dynamics and Control Theory Course at YYY.** The pendulum was utilized in two sections of the Dynamic System and Control Theory course (ME 3501), taught by the principal investigator. Section 1 has 40 students enrolled, and Section 2 has 36 students. We developed 20 lab kits by 3D printing key components such as the supports and the pendulum at a tabletop 3D printer using PLA filament. Each kit also includes an Arduino, cables, and magnets to serve as tip loads. The learning activity is based on the POGIL model and is similar in structure to prior activities we have designed. The learning objectives are: modeling of a SDOF system, reading data from an encoder using Arduino and MATLAB, simulation the system in MATLAB Simulink, and comparing the simulated response with experimental data.

**Student Response:** Data from a Student Assessment of Learning Gains survey was collected from both sections and is summarized in Table 1. Quality of contact with the instructor and working with peers received the highest average ratings from the students. The students generally reported the assignment provided moderate amounts of help in their engineering skills development.

**3.2 Inverted Pendulum Control Equipment.** We designed a SDOF controlled pendulum as shown in Fig 2 to explain the working principles of an encoder, a DC motor, and a motor driver, along with their roles in the control system. Students were asked to explain the importance of the feedback control mechanism in stabilizing the pendulum arm; develop, simulate, and test a PID control algorithms to stabilize the system; adjust parameters for optimal performance; implement feedback control via a microcontroller; employ sensors and actuators; and validate the experimental results by comparing them with virtual simulations. This equipment helps the students understand the critical importance of controlling the position of a pendulum arm, which is analogous to many mechanical operations such as levers and beams.

Table 1: Student response to simple pendulum activity

| SALG ITEM | Average Rating (scale 1-5) Section 1/ 2 |
|---|---|
| Overall Learning Environment<br>• Mental stretch required<br>• Quality of contact with instructor<br>• Working with peers on assignment | <br>• 2.9 / 3.5<br>• 3.4/3.9<br>• 3.7/3.8 |
| Engineering Skills Development<br>• Defining problems<br>• Breaking down and analyzing problems<br>• Solving problems | <br>• 3.2/3.4<br>• 3.4/3.6<br>• 3.3/3.6 |

**Implementation of The Inverted Pendulum.** We built four setups of the same setups to be utilized in the Embedded Digital Systems course at Kennesaw State University and four setups for the Introduction to Robotics Systems lab course at the University of Michigan-Dearborn for a team of 4 and a total of 23 students. The learning objectives for inverted pendulum learning activity are (1) explaining the working principles of system components such as encoder, DC motor, and a motor driver, (2) explaining the importance of the feedback control mechanism in stabilizing the pendulum arm, (3) simulating and testing control algorithms (such as PID control), (4) implementing a feedback control system using microcontroller, employing sensors and actuators to stabilize the inverted pendulum, and (5) validating experimental results by comparing them with virtual lab simulations. The learning activity starts with performing system identification of the system where velocity data is collected for different input signals and a second-order transfer function is estimated in the MATLAB System Identification tool. Then, a Simulink model is created to test the step response of the system with the obtained transfer function model. A PID control algorithm is implemented on Arduino Uno to test and observe different sets of PID coefficients that impact system stability, response time, and steady-state error. The students also analyze how changing the sampling period affects control performance.

**Student Response:** Data from a Student Assessment of Learning Gains survey was collected from the courses at two institutions: Kennesaw State University and University of Michigan Dearborn.

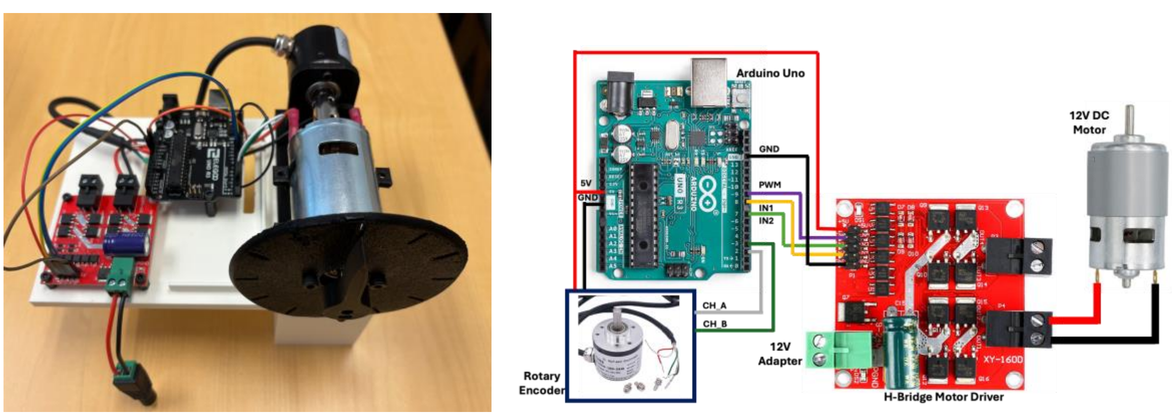


Figure 2. Inverted Pendulum Lab Kit and its Hardware Electrical Connection Diagram

Table 2: Student response to controlled pendulum activity

| SALG ITEM | Average Rating (scale 1-5) |
| --- | --- |
| Overall Learning Environment<br>• Way in which material was approached<br>Engineering Skills Development<br>• Defining problems; Solving Problems<br>• Understanding real-world relevance | <br>• 3.8<br><br>• 3.7<br>• 3.7 |
| Confidence<br>• Understanding underlying theory/concepts<br>• Confidence in ability to explain theory<br>• Develop, simulate, and test control algorithms | <br>• 3.4<br>• 2.8<br>• 2.8 |

As shown in Table 2, the students reported benefiting from the way the material was approached and that the learning activity generally improved their ability to define and solve problems. The area of conceptual understanding that was most solidified for students through the completion of this learning activity was understanding the relevance of this topic to real world issues. However, while students generally reported moderate confidence in understanding the theory, they reported only marginal confidence in their ability to explain the theory and develop their own control algorithms as a result of this learning experience. Four out of the seven students who left comments had positive remarks about the learning activity. These students mentioned that the learning activity was “useful”, “helpful”, “enjoyable”, and a “very good lab.” The other 3 student comments reflected challenges with the equipment and completing the lab in the time given.

**3.3 Control Theory Virtual Lab Simulations.** Our previously designed open-source virtual lab simulations were created for undergraduate-level control theory courses and are available for download from the project’s GitHub website [16] and MATLAB FileExchange [17]. The virtual lab simulations were given as a first-week lab activity for the Introduction to Robotics Lab at the University of Michigan-Dearborn.

**4. Conclusion.** We implemented a previously designed pendulum and a new control lab design at our home institution, and the new control lab equipment and virtual lab simulations at an external institution. The project will continue engaging with different institutions while developing new open-source AI assisted control packages. Also, student ambassadors from the PIs’ research group will contact student organizations to increase the engagement. Progress in testing the impact of full learning packages was made with the free pendulum kit, and data from that work regarding the use of AI assistance was also collected.

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