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A Hybrid Simulation Approach to Overcome Equipment Constraints in Engineering Labs

Dr. Getachew Ambaye, Austin Peay State University

Getachew Ambaye is an Assistant Professor of Engineering Technology at Austin Peay State University in Clarksville, Tennessee. He earned his Ph.D. in Industrial and Manufacturing Engineering from Wichita State University and holds both master's and bachelor's degrees in mechanical engineering from Jimma Institute of Technology. His teaching and research focus on fluid power systems, solid mechanics, design of machines, soft robotics, simulation, and structural health monitoring using machine vision and structural digital experimentation tools.

Yimesker Yihun, North Carolina A&T State University
Mr. Matthew S. Anderson, Austin Peay State University

Professor Matthew S. Anderson is an Assistant Professor in the Engineering Technology department at Austin Peay State University in Clarksville, TN. Professor Anderson's academic interests are in the field of Mechatronics, and he has completed up through Level 3 SMSCP training with Siemens. He has been a full-time faculty member at Austin Peay State University since 2016 and is currently working towards obtaining tenure while serving as the Mechatronics concentration coordinator in the Engineering Technology department. Additionally, he is currently completing the final year of an EdD in Educational Leadership. Other research interests include Industry 4.0, regional workforce development, and gender disparities in the engineering fields.

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Abstract

Hands-on laboratory experience is essential to develop conceptual understanding in engineering technology education; however, limited access to physical training equipment often constrains student engagement and learning. To address this challenge, this study presents a hybrid laboratory approach that integrates a simulation-based learning environment to supplement traditional physical laboratories. The simulation platform enables students to independently construct, modify, and troubleshoot hydraulic circuits in a virtual environment prior to in-person laboratory sessions. The instructional implementation follows a structured three-phase model consisting of pre-lab simulation activities, rotational access to physical equipment, and post-lab reflection and analysis. This approach improves laboratory efficiency while supporting deeper conceptual understanding by preparing students for hands-on experimentation. The preliminary results indicate increased student preparation, reduced cognitive load during laboratory activities, and improved student engagement. These findings suggest that the integration of simulation-based learning offers a scalable and effective solution to equipment access limitations and represents a valuable pedagogical strategy for engineering technology education.
Keywords: Fluid power; Hydraulic simulation; Electro-pneumatics; Hands-on learning; Experiential learning

1. Introduction

Enhancing teaching and learning in engineering education has motivated the adoption of a wide range of instructional strategies aimed at improving student engagement and conceptual understanding. Previous research has demonstrated the effectiveness of Project-Based Learning (PBL) in promoting deeper learning and design competence [1], flexible plug-and-play active learning approaches that support adaptability across instructional contexts [2], and the integration of AI-based scaffolding to improve critical thinking and self-directed learning [3]. In parallel with these pedagogical approaches, the use of software-based instructional tools has been increasingly recognized as an important mechanism to foster interactive and student-centered learning environments.

Simulation software provides an effective platform for studying the behavior and dynamic response of physical systems through accurate digital representations [4–6]. These tools offer significant flexibility by allowing learners to adjust performance parameters, explore design variations, and analyze system responses without incurring material costs or exposing users to safety risks. One of the primary advantages of simulation-based learning is that users can experiment freely in a virtual environment without the risk of physical damage [7], making it a safe and cost-effective approach for education and system development. Such environments are particularly valuable in instructional settings where access to physical laboratory resources is limited.

Simulation-based instruction can complement, rather than replace, traditional hands-on laboratory activities by providing learners with an affordable and low-risk environment in which they can experiment, explore system behavior, and develop conceptual and procedural knowledge prior to physical implementation [8]. Despite these advantages, simulations do not always perfectly replicate real-world behavior. Physical systems may exhibit deviations due to factors such as ambient temperature fluctuations, uncontrolled vibrations, component wear, manufacturing tolerances, and environmental disturbances. Consequently, simulation results should be interpreted with awareness of these inherent limitations and, when possible, validated through experimental implementation to reinforce learning transfer.

In the context of hydraulic power systems, simulation software plays a particularly critical role. Hydraulic circuits often involve complex interconnections between multiple components, operate under high pressures, and may present safety hazards due to fluid leakage or component failure. Simulation environments allow students to design, analyze, and verify hydraulic circuits in a clean and controlled environment, ensuring compliance with design standards while accounting for reasonable levels of uncertainty. The widely used simulation tools for fluid power education and research include MATLAB Simscape Fluids [9], FluidSIM [10], and related platforms.

Simulink-based modeling and simulation tools have been widely adopted in engineering education and research. Previous studies have shown that Simulink-based instructional activities can significantly improve the understanding of fundamental concepts of thermodynamics and fluid mechanics by students [11]. These approaches have also been extended beyond higher education contexts by integrating simulation results into accessible computational tools, enabling broader engagement with complex engineering systems.

Fluid power is a core engineering subject that integrates principles of solid mechanics, fluid mechanics, electrical components, and control logic. Due to its multidisciplinary nature, effective instruction requires a combination of teaching approaches that promote system-level thinking and a deeper conceptual understanding. Hydraulic circuits have also been successfully used as instructional analogies to illustrate basic electrical concepts, further strengthening cross-domain learning and conceptual transfer [12, 13]. In this context, hybrid instructional approaches that strategically combine simulation-based learning with hands-on laboratory experiences offer a promising pathway to improve student learning while addressing practical constraints related to equipment availability and instructional efficiency [14].

From a learning-theory perspective, pre-laboratory simulation activities can reduce extraneous cognitive load by allowing students to become familiar with the components and behaviors of the system prior to physical experimentation, thus improving learning efficiency [15]. Additionally, the structured progression from simulation to hands-on experimentation and post-laboratory reflection is aligned with experiential learning theory, which emphasizes learning through concrete experience, reflection, and active experimentation [16].

2. Methodology

The Electro-Pneumatic and Hydraulic Control course relies on a physical AMATROL hydraulic training system [17] to provide students with hands-on experience in circuit design, component behavior, and system operation. Although this equipment is essential for developing practical skills, instructional delivery is limited by limited resources. In the current course configuration, a single hydraulic trainer is shared by approximately twelve students, resulting in restricted hands-on time per student, increased waiting periods, and reduced opportunities for experimentation. These constraints often create pressure to complete tasks quickly, which can limit conceptual understanding and meaningful engagement with hydraulic principles.

To address these challenges, a desktop-based hydraulic simulation environment was developed using Python bindings for the Qt5 framework (PyQt5) [14]. This framework is open-source, cross-platform, and widely supported within the scientific and engineering computing communities. Its modular architecture allows for flexible graphical interface design, real-time parameter manipulation, and extensibility for additional hydraulic components and analysis features. The methodological focus of this study is not on the software architecture itself, but on the instructional integration of simulation-based activities and their impact on students' understanding of hydraulic systems. The simulator provides a virtual, interactive environment in which students can assemble hydraulic circuits, modify component configurations, and observe system responses under varying operating conditions. Visualization of flow paths, pressure changes, and valve actuation enables students to explore behaviors that are often difficult to observe directly during time-limited physical laboratory sessions.

The instructional methodology follows a structured progression from virtual engagement to physical experimentation. Prior to laboratory sessions, students interact with the simulation software to explore hydraulic components, understand functional relationships, and test multiple circuit configurations in a low-risk environment. This preparatory phase is intended to reduce cognitive load during physical labs by familiarizing students with component functions, expected system responses, and common troubleshooting scenarios. During subsequent laboratory sessions, students apply this prior virtual experience to the physical AMATROL trainer, enabling more efficient use of limited equipment time and deeper engagement with system-level behavior.

This virtual-to-physical progression supports independent learning by allowing students to experiment freely, make mistakes, and iterate on designs without risk of equipment damage or time pressure. Simulation is positioned as an instructional scaffold rather than a replacement for physical laboratories, preserving the essential role of hands-on experimentation while strengthening the connection between theory and practice.

2.1 Implementation Structure of the Hybrid Laboratory Approach

Figure 1 presents an overview of the hybrid laboratory workflow, while Table 1 outlines the corresponding instructional stages and their intended roles.

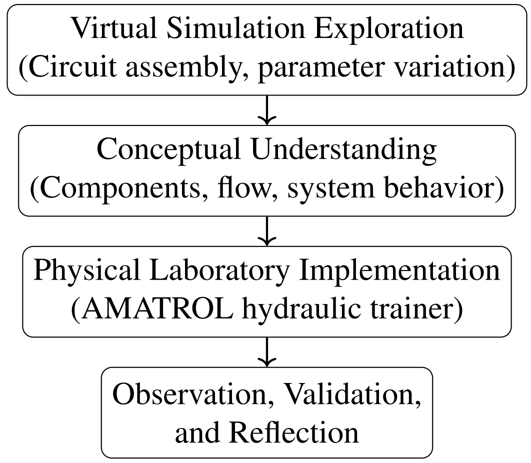

Figure 1: Methodological flow illustrating the progression from simulation-based preparation to physical laboratory implementation and reflective learning.

Table 1: Methodological Stages, Learning Activities, and Instructional Purpose

Methodological Stage	Learning Activity	Instructional Purpose
Pre-lab simulation	Circuit assembly and parameter variation using the simulator	Develop conceptual understanding and system intuition
Guided experimentation	Exploration of valve inputs, flow paths, and system response	Foster independent learning and experimentation
Physical laboratory session	Implementation on the AMATROL hydraulic trainer	Apply concepts in an authentic, hands-on environment
Reflection and comparison	Comparison of simulated and physical system behavior	Reinforce theory–practice connections

2.2 Limitations

Several limitations of this methodology are acknowledged: First, simulation-based activities cannot fully replicate the tactile feedback, noise, and physical constraints of real hydraulic systems, and therefore cannot substitute for hands-on laboratory experience. Second, the effectiveness of the approach depends on the participation of the students in the simulation during the preparatory phase; Insufficient participation may reduce its instructional benefit. Finally, results from this implementation are influenced by the course context and equipment availability, which may limit direct generalization to courses with different laboratory infrastructures. These limitations are mitigated by positioning simulation as a preparatory scaffold rather than a replacement for physical laboratories and by integrating structured guidance and reflection into the instructional sequence.

Although this study implemented a custom PyQt5-based hydraulic simulator to provide full transparency of the parameters, instructional control, and extensibility, the proposed three-phase instructional methodology is platform-agnostic. Specifically, the sequence of (1) guided conceptual grounding, (2) structured simulation-based exploration, and (3) reflective physical implementation can be implemented using commercially available simulation platforms when instructors cannot develop custom tools. Examples include widely adopted fluid power simulation platforms, such as Simscape Fluids [9] and FluidSIM [10], which provide integrated environments for parameter variation, dynamic system visualization, and scenario-based performance evaluation. Consequently, the primary contribution of this work lies in the pedagogical scaffolding and sequencing strategy rather than dependence on a single software implementation, increasing transferability between institutions with diverse technical resources.

2.3 Software Accessibility and Deployment

A key advantage of the developed simulation environment is its accessibility beyond the physical laboratory space. The PyQt5-based application is distributed to students for installation on their own personal devices, allowing independent exploration outside of scheduled class and laboratory sessions.

This deployment model supports multiple instructional contexts:

- In-class guided demonstrations,
- Structured pre-laboratory assignments,
- Post-laboratory reflection and troubleshooting exercises,
- Independent scenario testing and parameter exploration.

By allowing students to install and run the simulator locally, the instructional model reduces the reliance on limited laboratory hardware and extends learning opportunities beyond fixed scheduling constraints. This flexibility directly addresses common equipment-access challenges in Engineering Technology programs while preserving the essential hands-on laboratory experience.

3. Hybrid Laboratory Implementation

The hybrid laboratory implementation operationalizes the simulation-supported instructional framework through a structured sequence of activities integrated into scheduled laboratory sessions. The implementation is organized into three coordinated phases, simulation preparation, physical laboratory execution, and post-laboratory analysis designed to ensure continuity between virtual and physical learning environments. Figure 1 provides an overview of the implementation flow.

3.1 Phase 1: Simulation Preparation

Before the scheduled laboratory session, students complete simulation-based activities using the developed hydraulic simulation environment [14]. These activities require students to assemble hydraulic circuits aligned with planned laboratory experiments, configure component parameters, and observe system responses under varying operating conditions. Simulation tasks are completed individually or in pairs and include guided prompts to encourage exploration of flow behavior, actuator motion, and valve operation. This preparatory phase ensures that students enter the physical laboratory with prior exposure to circuit layouts and expected system behavior, enabling a smoother transition to hands-on implementation.

3.2 Phase 2: Physical Laboratory Execution

During the laboratory session, students implement the same hydraulic circuits on the physical training equipment. To accommodate limited equipment availability, students rotate through hands-on laboratory stations in small groups. While one group performs physical implementation and system operation, the remaining groups continue to perform simulation-based analysis or review circuit behavior.

Students operate the hydraulic system, adjust control parameters, and observe actuator motion, pressure response, and flow characteristics. Emphasis is placed on reproducing simulation-configured circuits and verifying the behavior of the system through direct observation. Instructor interaction during this phase focuses on facilitating troubleshooting, confirming correct implementation, and guiding comparison between simulated and physical responses.

3.3 Phase 3: Post-Laboratory Analysis and Reporting

Following completion of the physical laboratory activities, students conduct post-laboratory analysis to compare simulation results with experimental observations. This analysis includes identifying discrepancies between predicted and observed behavior, explaining potential sources of variation, and validating system performance through measured responses.

Students document their findings in structured laboratory reports that integrate simulation screenshots, experimental observations, and an explanatory discussion. This phase formalizes the connection between simulation and physical implementation and reinforces system-level understanding through documentation and analysis.

3.4 Implementation Considerations

The hybrid laboratory implementation is designed to be modular and adaptable to different instructional settings. Simulation activities are aligned directly with laboratory objectives, and the rotational structure allows the approach to scale to varying class sizes and equipment availability. Physical laboratory activities remain central to implementation, and simulation serves as a preparatory and analytical tool that supports efficient and effective laboratory execution.

3.4.1 Representative Simulation-to-Laboratory Demonstration

To illustrate the execution of the hybrid laboratory implementation, a representative simulation-to-laboratory demonstration was conducted using meter-in and meter-out hydraulic flow control systems. These configurations were selected due to their relevance in hydraulic applications and their suitability for examining the relationship between flow rate, actuator motion, and pressure behavior.

In the simulation phase, students constructed a meter-in hydraulic circuit, as shown in Fig. 2. The virtual configuration included a hydraulic power unit, directional control valve (DCV), flow control valve, pressure relief valve, and a double-acting hydraulic cylinder. The simulation environment enabled modification of key system parameters, including actuator stroke length, bore and rod diameters, and electric motor speed. Adjusting the motor speed directly affected the pump flow rate, allowing students to explore actuator behavior under varying flow conditions. For this exercise, the

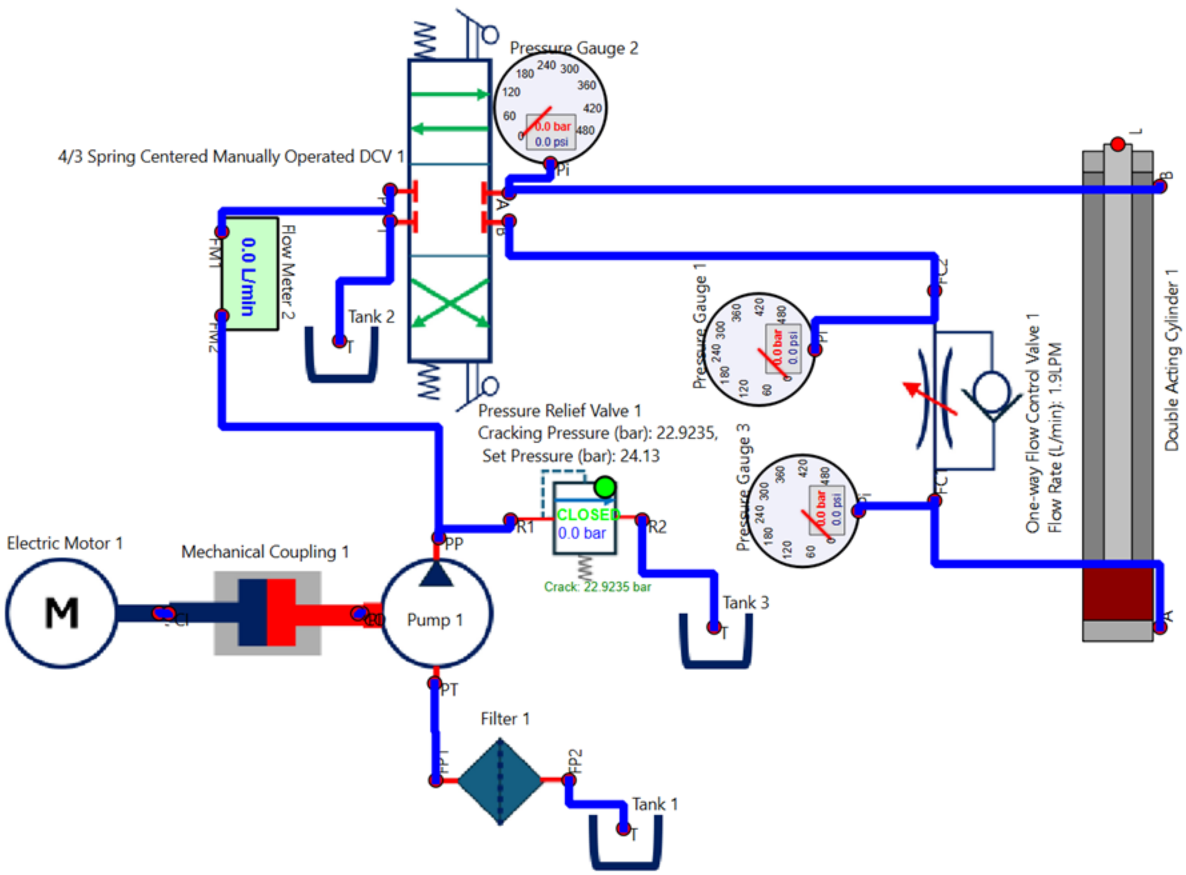

Figure 2: Meter-in flow control hydraulic circuit

pressure relief valve was configured with a set pressure of 24.13 bar, and the flow meter regulated via the flow control valve indicated a flow rate of 1.9 L/min. The actuator parameters were specified as follows: stroke length of 100 mm, bore diameter of 50 mm, and rod diameter of 20 mm. These parameters were selected to maintain consistency with the physical laboratory hardware while enabling clear observation of system response.

To evaluate actuator performance in the meter-in configuration, the actuator responses position, velocity, and acceleration were recorded, as illustrated in Fig. 3. The piston rod was initially fully retracted, corresponding to a linear position of 0 mm. Upon shifting the DCV spool from the center position to the extension position, the actuator extended from 0 to 100 mm, as shown in Fig. 3(a). When the spool was shifted to the opposite position, the actuator retracted to its initial position.

The recorded velocity response indicates that the actuator extended at an average velocity of approximately 16.2 mm/s when the DCV spool was shifted to the extension position, and retracted at approximately 19.2 mm/s when the spool was shifted in the opposite direction, as shown in Fig. 3(b). Additionally, the simulation provided a clear visualization of acceleration transients at the beginning and end of each stroke, which are evident as spikes in the acceleration response shown in Fig. 3(c). Following completion of the simulation, students implemented the same hydraulic circuit

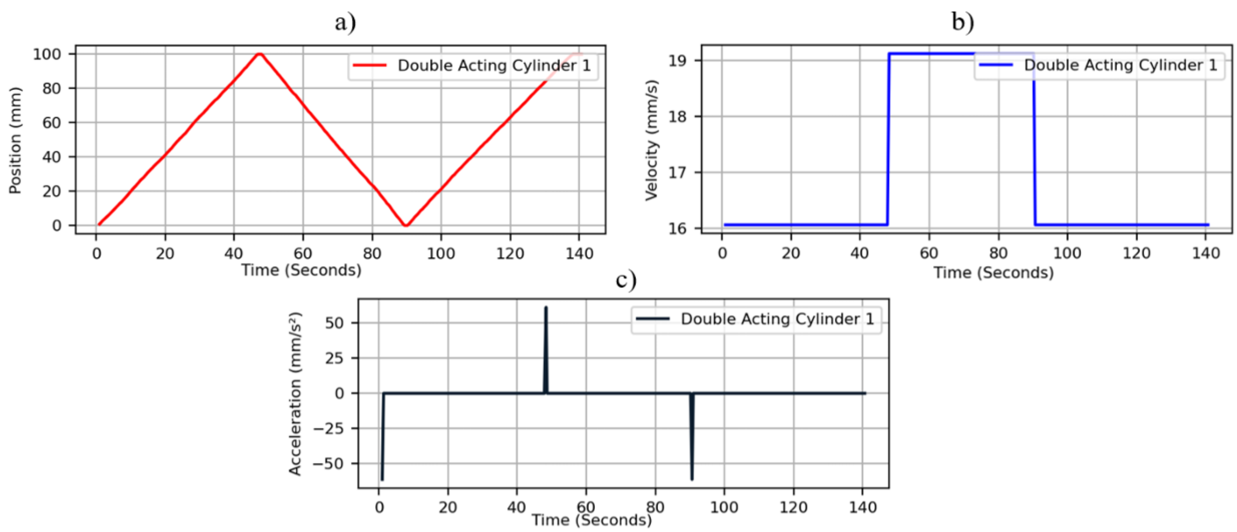

Figure 3: Actuator responses of the meter-in system

on the physical training system. The physical setup mirrored the simulated configuration, and valve settings were adjusted to match the simulation parameters. Actuator motion and pressure readings observed during physical operation were compared directly with simulation results to verify system behavior and identify deviations arising from real-world effects such as friction and component tolerances.

3.4.2 Pressure-Reducing Valve Circuit Exercise

A second representative laboratory exercise focused on the operation and integration of a pressure-reducing valve within a hydraulic circuit. This activity corresponds to Skill 6 in the Amatrol Basic Hydraulics Trainer module and was selected to provide students with hands-on experience using components commonly encountered in industrial hydraulic systems. The instructional setup included a directional control valve, check valve, pressure-reducing valve, needle valve, and a double-acting hydraulic cylinder.

The students initially developed and analyzed the circuit using the simulation environment. During this phase, the system pressure was set to prescribed values, and pressure measurements were taken at two locations within the circuit: upstream of the pressure reducing valve and downstream of the valve. This configuration allowed students to observe the pressure-reduction effect directly and examine how the valve maintains a regulated downstream pressure independent of variations in upstream supply pressure. The simulation was also used to study the behavior of cylinder extension and retraction under different pressure and flow settings.

Following completion of the simulation-based analysis, the students implemented the same circuit on the physical hydraulic trainer. The physical setup mirrored the simulated configuration, allowing students to operate the double-acting cylinder, adjust the pressure reducing valve, and monitor the response of the system. The measured pressures and observed actuator motion were compared with the simulation results to verify the system behavior. This implementation reinforced consistency between simulated predictions and physical operation, while exposing students to practical considerations such as valve adjustment sensitivity and real-world system response. Representative simulations and physical implementations of this exercise are shown in Fig. 4.

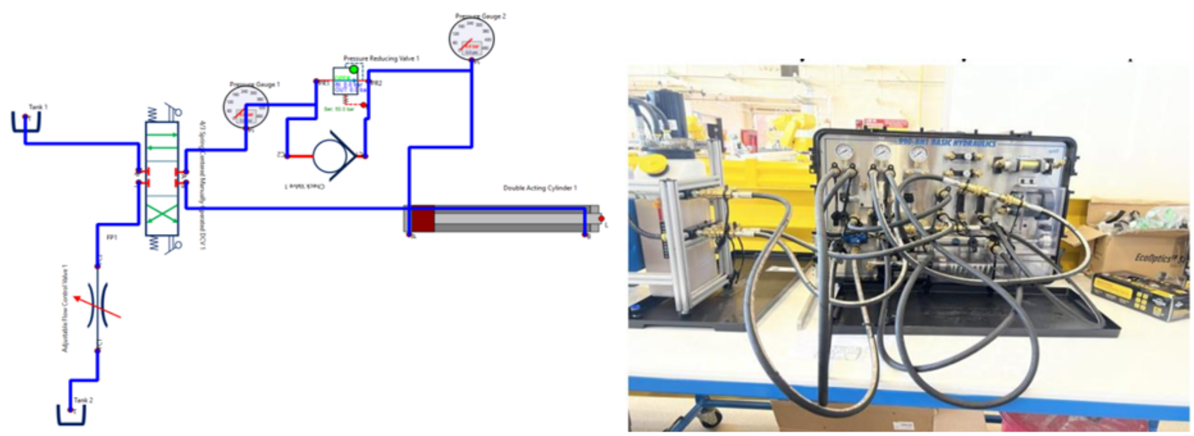

Figure 4: Student work sample: Simulation hydraulic circuit (left); Physical hydraulic circuit (right)

3.5 Learning Impact and Assessment

To evaluate the impact of the implementation of the hybrid laboratory on the conceptual understanding of the students, a targeted formative assessment was administered before and after the completion of the simulation-based and physical laboratory activities. Following theoretical instruction and in-class exercises on pumps and actuators, particularly emphasizing the relationship between flow rate and actuator motion, students were asked a conceptual question requiring them to predict actuator behavior in response to an increase in flow rate.

The results of the pre-laboratory evaluation indicate that approximately 70% of students correctly identified that increasing the flow rate would result in an increase in actuator speed, while the remaining 30% selected incorrect responses, including “no effect” or “decrease actuator speed,” as shown in Fig. 5. These results suggest that, despite previous theoretical instruction, a substantial portion of the students had incomplete or incorrect conceptual understanding prior to participating in laboratory activities. After completing the simulation-based exercises and the corresponding

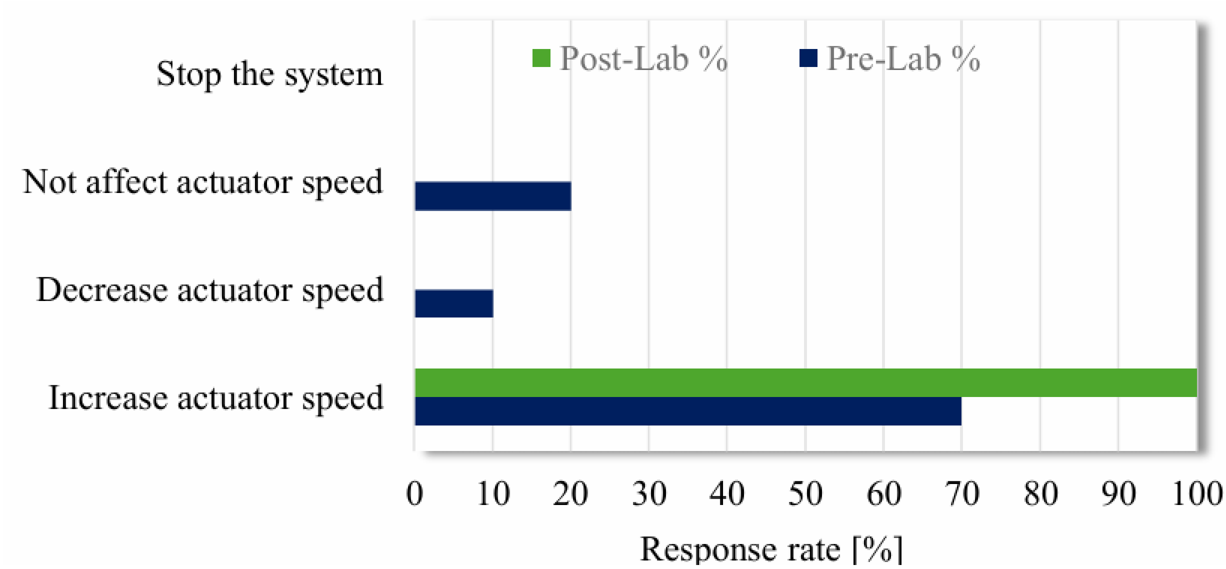

Figure 5: Pre and post responses for the question “Increasing flow rate will generally”

physical laboratory implementation, the same conceptual question was administered again. In the post-laboratory assessment, all students (100%) selected the correct response, indicating a clear improvement in conceptual understanding. Importantly, the question was not explicitly discussed between the pre- and post-assessments, suggesting that the observed improvement can be attributed to the hybrid laboratory experience rather than direct instructor intervention.

In addition to conceptual assessment, student perceptions of the instructional approach were collected through a post-laboratory survey. The results indicate a strong preference for simulation-based learning as a preparatory tool. Specifically, 90% of respondents reported that the simulation was “more effective” than traditional lectures or demonstrations in helping them visualize system behavior and component interactions, while the remaining 10% indicated that it was “about the same.” No respondents rated the simulation as less effective. These responses suggest that the simulation environment improved the confidence and willingness of the students to explore the behavior of the system in a safe and low-risk setting.

The students were also asked to evaluate to what extent the simulation helped them connect theoretical concepts with the operation of real hydraulic systems before working on the physical trainer. The survey results show that 85% of the students reported that the simulation helped them “very much” in making this connection, while the remaining students indicated that it helped them “moderately.” These findings indicate that the simulation-based activities were effective in bridging the gap between theoretical instruction and hands-on system operation.

In general, the results of the evaluation demonstrate that the implementation of the hybrid laboratory supported measurable gains in conceptual understanding and was positively perceived by the students as an effective instructional approach. Although the sample size is limited and no control group was employed, the consistent improvement observed across conceptual and perception-based measures suggests that integrating simulation based preparation with physical laboratory experiences can meaningfully enhance learning in fluid power education.

4. Conclusions

This paper presented a hybrid laboratory approach that integrates simulation based learning with traditional hands-on experimentation to address equipment access constraints in engineering technology education. Simulation activities were embedded as preparatory and analytical components aligned directly with the physical laboratory implementation. Two representative laboratory exercises with meter-in flow control and pressure-reducing valve applications were used to illustrate the approach.

The results of the evaluation indicate significant improvements in conceptual understanding after participating in the hybrid laboratory activities. In post-laboratory evaluation, 100% of the students correctly predicted actuator behavior in response to an increase in flow, compared to approximately 70% prior to laboratory experience. Additionally, about 90% of students reported improved understanding and engagement, and 85% indicated that simulation activities strongly supported their ability to connect theory with physical system operation.

These findings suggest that simulation-based preparation can enhance the effectiveness of hands-on laboratories while supporting efficient use of limited resources. The study is limited by a small sample size and the absence of a control group. Future work will expand the fidelity of modeling, incorporate pneumatic systems, and deploy the framework in multiple offerings to further evaluate learning outcomes.

Future work will scale this pilot into a larger quasi-experimental study to evaluate the three-phase methodology. The design will compare course sections using the three-phase approach (concept instruction, simulation scaffolding, physical lab execution) with sections using a traditional lab-first approach without structured simulation scaffolding.

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