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PAPER

Evaluation of the Developed Stepper Motor Control Lab for Undergrad Microcontroller-Robotics Education

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ABSTRACT

This study evaluated the developed cost-effective stepper motor laboratory equipment for undergraduate engineering students, addressing the challenges of financial constraints and limited lab access. Utilizing the ADDIE model, the equipment was designed to support basic to intermediate microcontroller-robotics applications through five experiments. Student performance was assessed by comparing traditional practice, simulations (Tinkercad), and the actual lab equipment across three lab activities, revealing significant improvements with the physical setup. For the remaining two experiments, where Tinkercad lacked the necessary components, a mixed-methods approach was employed. Quantitative survey results demonstrated strong agreement and satisfaction, with Cronbach's alpha exceeding 0.90, confirming reliability. Qualitative thematic analysis, using Braun and Clarke's 6-step method, highlighted user-friendliness and component-specific features as key strengths. Minor suggestions primarily focused on improving physical design. These findings validated the effectiveness of the developed stepper motor lab equipment in enhancing practical learning and bridging the gap between theoretical knowledge and microcontroller-robotics applications, particularly by overcoming the limitations of simulation-only learning.

KEYWORDS

engineering education, stepper motor, engineering laboratory, undergraduate education, manufacturing engineering

1 INTRODUCTION

Traditional laboratories (TL) have long been essential to scientific engineering and technological education, providing a vital space for translating theoretical concepts into practical applications. This is characterized by the use of physical laboratory facilities or lab equipment, supported by actual experimentation and professional instruction. Additionally, the laboratories contributed to the knowledge, practical skills, and expertise of the students profoundly [1]. With this actual engagement with the lab materials, the students will patently improve their critical

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thinking, problem-solving, and technical aptitude, contributing to their success in their respective disciplines [2]–[4].

Indeed, the efficacy of conventional laboratories in engineering and engineering technology is distinguished [5]–[8]. Active experimentation nurtures a deeper understanding of theories and principles, bridging the gap between learning in the classroom and real-world application [9]–[13]. Moreover, the laboratories promote learning through collaboration or teamwork, communication, and skills in problem-solving, which parallels the professional engineering circumstances [14]–[16]. Furthermore, the experience gained by the students will prepare them for their career paths, such as research, industry, or academia.

Despite the success of hands-on learning at conventional laboratories [17], it also faces certain challenges. Frequently, this type of laboratory requires a substantial amount of investment to establish [18]–[23]. Since expenditures associated with these laboratories, such as acquisition, maintenance, and upgrade, are exorbitant, some institutions cannot access nor procure up-to-date lab equipment [24]. Correspondingly, a dedicated physical area, safety equipment, consumable materials, and utilities are needed and add to the economic burden of the institution.

Limited access to laboratory equipment is another challenge [11], [21], [25]–[27] due to its requirements, such as space, time, and equipment availability. In some cases, a laboratory can be accessed by a student or a group of students in a limited time frame, which requires multiple sessions for the batch or a section to accommodate [19], [28]. The effect will be a reduction in their exposure or actual time in laboratory activities, resulting in unrefined skills or abilities of the students. Also, when students share laboratory equipment, problems regarding delays, actual experiment time reduction, and frustration are inevitable [15]. This also hampers the learning process, as it gives students minimal time to explore their work.

In this study, the problem of financial constraints and limited laboratory access was addressed by designing low-cost and effective stepper motor laboratory equipment. The study conducted a comparative analysis of simulation-based versus actual lab-based performance for the first three experiments. The remaining lab experiments and activities were evaluated using a mixed-methods approach, which encompassed both quantitative survey questionnaires and qualitative thematic analysis.

2 LITERATURE REVIEW

Truly, TL has been associated with the practical learning of the students, as it provides the learners with access to precise instruments, which is valid for handling experiments, data analysis, and troubleshooting in real-life setups [5], [7], [29], [30]. For example, in the case of the disciplines connected to manufacturing, such as robotics, automation, and motor controls, one delicate motor is the stepper motor. This type of motor provides precise rotation, making it suitable for critical operations. For students, learning its usage, dynamics, and motion will be a great advantage, especially in these times of modern manufacturing. However, the establishment: procurement of new models; maintenance: calibration, repairs, parts replacement; and upgrades produce financial barriers for institutions. Instead, institutionalizing the designing and developing of a TL setup will reduce financial constraints and improve educational output for students, as the whole process will be student-centered.

In line with these circumstances, there are studies in which researchers and educators design and develop their laboratories to address the nonexistence of a specific lab or upgrade or support existing labs with accurate output. For instance, the low-cost IoT labs created by Madona et al. (2022) [19] and Bye and Osen (2019) [31]; the low-cost digital signal processing lab of Maina et al. (2016) [22]; the low-cost Programmable Logic Control (PLC) training set of Sunomo and Asmara (2019) [24]; the low-cost Arduino-based education tool of Oliveira et al. (2019) [11] and De Moura Oliveira et al. (2021) [32]; and the low-speed wind tunnel lab of Siregar and Umurani (2019) [21]. The researchers achieve cost-effective labs that use not only modular designs but also open-source technologies such as Arduino or Raspberry Pi. Moreover, low-cost labs offer several advantages, including increased accessibility for financially constrained institutions [19], [24], [26] and distant learners [28], valuable hands-on experience in assembly [15], troubleshooting, and programming [11], [22], and sustainability through designs that support reuse and versatility [31].

Comparably, virtual laboratories (VL), which can be called non-traditional labs (NTL), have emerged as an alternative to TL [33]–[36], where logistic barriers such as inadequate space [25], conflict in scheduling, and external disruptions such as pandemics occur [27]. VLs' main objective is to replicate TL by bringing them online. In an online setup, the students can conduct their simulations, animations, and experiments remotely in their homes or wherever they are located as long as they have the necessary materials for the activities. Some of these NTLs include the work of Fukumoto et al. (2021) [28], where they developed remote simulations of stepper motor lab activities. Similarly, various studies [18], [20], [23], [29], [37] designed web interfaces to allow students to access the laboratory online. Although the benefits parallel the TLs, some aspects are compromised, such as the hands-on experiences, which are critical in the development of practical skills [5], [7], [11], [29]. Further long-term research should be done to evaluate if the virtual labs not only parallel with the skills outcome of the students but also a good opportunity to look into other factors such as the emotion and passion of the students and instructor, attitude and affection during group work.

Additionally, in line with the results of different studies, first, the design of the IoT lab kit of Madona et al. (2022) [19] provides the advantage of portability to students and low cost to the institution. While in the work of Oliveira and Hedengren (2019) [26], students provided favorable feedback regarding the accuracy of measurements and corresponding safety in their developed laboratory. According to Zine et al. (2019) [23] and Brinson (2015) [29], there are no significant differences in the academic performance of students between NTL and TL. Then, laboratory effectiveness to students in developing critical thinking and problem-solving skills is demonstrated through the works of Berman et al. (2021) [9] as they perceived enhancement of ability in system performance and troubleshooting. Furthermore, using individual lab kits ensures active engagement from all students [15]. Students showed substantial improvement in post-test scores compared to pre-test scores as a result of using their developed lab equipment [11], [28]. Additionally, the study by Bye and Osen (2019) [31] revealed that graduates whose laboratory experience is limited would result in low performance in the professional space. Students constantly rated laboratory work as necessary to their learning experience [7], fortifying the value of practical learning in education [31].

Moreover, according to Fukumoto et al. (2021) [28], advanced evaluation is needed, which is utilizing a greater student number and conducting comparisons between TL and NTL to provide a more robust understanding of both. Then, the study of Berman et al. (2021) [9] suggests including more real-world situations in their practicum, which will lead to the enhancement of the student's practical skills and knowledge. Likewise, expanding the duration of hands-on sessions complemented with supporting resources like simulations would improve the exploration and learning experience of the students [9]. Furthermore, enhancements to lab equipment, materials, and infrastructure will be necessary for a more updated and conducive learning environment [7].

Lastly, only the work of Fukomoto et al. (2021) [28] paralleled to the development of a stepper motor lab. Others are the market-available products, such as various Arduino Kits [38], which are not only costly but do not have a stepper motor included. Compared with Fukomoto et al.'s work, their study enables remote access to a university stepper motor lab, whereas this study is limited to in-person laboratory sessions. In terms of hardware, their study utilized two Arduino boards (one for control and one for measurement), two stepper motors (one primary and one acting as a programmable load), and a Raspberry Pi camera. On the contrary, this study supports both basic and intermediate stepper motor applications, employing two types of stepper motors, advanced sensors, and Arduino boards for measurement and automation, thereby enhancing and advancing technical sophistication. Additionally, their study respondents were diverse, including third-year, fourth-year, and master's students assessed in a 1:1 student-to-lab-activity ratio [28], unlike this study, which conducts group-based assessments across four sections, limited to third-year students due to the capacity constraints of the developed stepper motor lab, which accommodates only two simultaneous groups.

Finally, regarding assessment, their study used and compared identical pretest and post-test questionnaires with eight multiple-choice questions on stepper motor principles, control, and programming [28], in comparison to this study, which employs an outcomes-based education (OBE) rubric for scoring simulation-based and laboratory-based assessments, enabling a more comprehensive evaluation of practical skills, deeper understanding, and alignment with real-world learning outcomes.

3 METHODOLOGY OF THE STUDY

The study employed a developmental model, specifically Analysis, Design, Development, Implementation, and Evaluation (ADDIE) [39], in developing the stepper motor laboratory equipment. The study found the model best suited as uncomplicated, direct, and easy to evaluate [40]. For the analysis phase, the motivation and technical specifications for the development of the lab equipment originated from insights gathered during stakeholder meetings. This was further reinforced by the recognized limitations of free applications such as Tinkercad, which notably lack stepper motor components in their digital libraries, highlighting a critical gap that the equipment aimed to fill. In the design phase, the study's design considerations aimed to facilitate both basic and intermediate learning applications of microcontrollers, recognizing that stepper motors are an integral component of robotics applications, which typically fall within the intermediate learning level. Accordingly, the design specifications and materials for the study were meticulously selected to align with these educational objectives. Next, for development phase, the chosen components were integrated in a manner that mirrored a flexible, reconfigurable system, allowing for simultaneous use and adaptability. This approach aimed to enhance the versatility of the lab setup. Then, for the Implementation Phase, the study involved students from the manufacturing engineering program who were enrolled in the Microcontroller/Microprocessor for MFE course. A total of 20 groups, each comprising five to six members, were formed across four sections, totaling 100 students. Five distinct experiments were prepared, with three designed for evaluating student learning progress through a comparison of simulation-based and actual-based scores. The remaining two experiments were specifically dedicated to exploring advanced stepper motors.

Lastly, for the Evaluation Phase, the performance of students in terms of simulation versus actual lab activity was evaluated using data from Experiments 1 through 3. Their scores were compared and validated through statistical analysis, specifically using one-sample t-tests and one-sample sign tests, after confirming the normality of the score data and ensuring that all corresponding assumptions were met. For the evaluation of the stepper motor module itself, students were instructed and given the opportunity to explore Experiments 4 and 5. A comprehensive survey instrument was utilized to assess their experience, acceptance, and insights regarding Prototype Functionality, Acceptability and Suitability, Aesthetics, Design and Safety, and Overall Satisfaction. The Likert items within this survey were subjected to item analysis using Cronbach's alpha to ensure reliability. Furthermore, a qualitative analysis using Braun and Clarke's 6-Step Thematic Analysis [41] was conducted to capture perceptions and insights regarding the strengths, weaknesses, and potential improvements of the developed laboratory equipment. Ultimately, the synthesis of results from this mixed-methods approach validated the overall effectiveness of the developed stepper motor laboratory equipment.

4 RESULTS AND DISCUSSION

4.1 Analysis

For the analysis section, the primary stakeholders for the developed stepper motor engineering lab are students in the manufacturing engineering program. The program's curriculum is designed to provide extensive knowledge of manufacturing practices, including robotics and automation. This requires practical and flexible hands-on experience to bridge theoretical knowledge and its application in real-world scenarios. Additionally, this study supports and addresses the identified concern at the last stakeholder meeting, in which alumni, private industry experts, faculty, students, and public officials participated. Among areas of concern, it is noted that the program should provide laboratory equipment parallel to simulation activities to improve knowledge, implement OBE output, and strengthen the integration of theory into practice. Students rely mostly on simulation-based activities using microcontrollers in online platforms such as Tinkercad. However, Tinkercad's limitations in simulating Arduino-related electronics, particularly stepper motor control, require dedicated lab equipment. Thus, this study designs a lab setup addressing basic to intermediate Arduino applications, including stepper motor-driven robotic systems, to provide a comprehensive, practical learning experience.

4.2 Design

In the design section, it focuses on basic to intermediate microcontroller applications for electronic components to enhance hands-on learning. Basic applications include breadboarding and wiring with consumables such as LEDs, resistors, capacitors, potentiometers, and basic ultrasonic sensors. Intermediate applications emphasize precise robot control using stepper motors, integrating advanced sensors such as Sharp IR sensors (used in vacuum robots) and PIR motion sensors, with breadboarding to combine components for comprehensive projects.

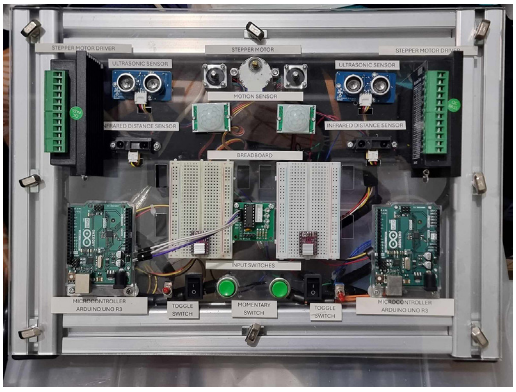


Fig. 1. Designed and developed stepper motor laboratory equipment

The lab equipment design incorporates a microcontroller, breadboard, momentary and toggle switches, ultrasonic sensor, Sharp IR sensor, PIR motion sensor, stepper motor driver, and stepper motor, all mounted on a durable, corrosion-resistant aluminum profile frame with 6 mm clear acrylic glass for activity transparency and durability, all shown in Figure 1. Mechanical prototyping involves customized 2D designs created in Corel, utilizing laser cutting technology for precision. Electronic components are bolted in place, and wires are intentionally extended to ensure flexibility for various educational activities.

4.3 Development

For the development, the block diagram in Figure 2 is similar to a feedback loop in control systems. The input includes various switches, such as momentary and toggle types. Next, the process involves programming the Arduino through the Arduino IDE.

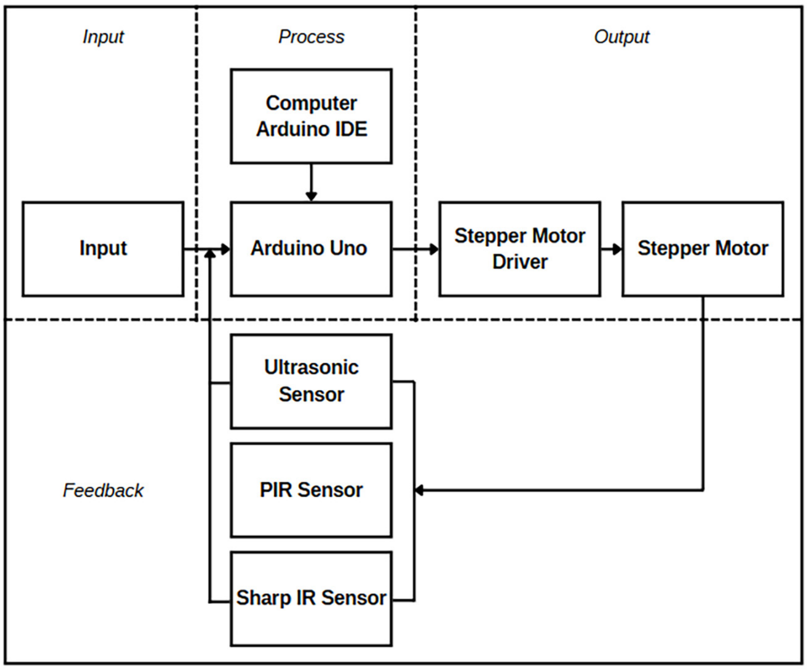


Fig. 2. Block diagram of fully functional developed stepper motor lab equipment

Then, the Arduino will control the stepper motor and serve as the output of the block diagram. Moreover, components, particularly sensors, can manipulate the stepper motor to achieve automation. While commonly available Arduino kits employ basic applications, this study develops a lab incorporating basic and intermediate applications in Arduino, such as robotics. Furthermore, the faculty can customize activities that align with the curriculum, such as IoT, robotics, and automation, since the lab equipment includes breadboards for dedicated wiring.

4.4 Implementation

For the implementation, students enrolled in Microcontroller/Microprocessor for MFE are involved in this study. The lab activities and experiments are designed to be completed by groups of five to six students, resulting in a total of 20 cumulative groups across four sections. Moreover, the study employed five experiments, as shown in Table 1.

Table 1. Laboratory experiment details, objectives, and competencies matrix

Experiment No. 1 **Relevance to Professional Field:** Manufacturing plant lighting system management to optimize costs and visibility. **Laboratory Class Experiment Equivalent:** Arduino-controlled LED lighting using Pulse Width Modulation (PWM) control.	
Experiment Objectives	**Target Competencies**
1. Develop an Arduino microcontroller program to manipulate the illumination of LEDs using a PWM signal through a potentiometer. **2.** Determine the power reduction value (using a multimeter), and calculate the resulting electrical consumption during the reduction of LED illumination.	**a)** Understand the Arduino microcontroller's architecture, including PWM-capable pins and analog-to-digital conversion (ADC) for interfacing with components. **b)** Design and assemble functional circuits integrating LEDs, potentiometers, resistors, and the Arduino, ensuring proper component ratings and connections. **c)** Calculate and analyze electrical power consumption, and measure circuit parameters using tools such as a multimeter.
Experiment No. 2 **Relevance to Professional Field:** Manufacturing production line transport conveyor system control using different switch modes [On/Off/E-Stop, (start, stop, emergency halt)]. **Laboratory Class Experiment Equivalent:** Arduino-controlled switch using Digital Input Pull-Up Function.	
Experiment Objectives	**Target Competencies**
1. Demonstrate the ability to configure and utilize a digital input pull-up circuit to control a switch-based system. **2.** Test and verify the stability and responsiveness of the On/Off and E-Stop functions to meet safety requirements in a production assembly environment.	**a)** Gain proficiency in configuring and troubleshooting digital input circuits, specifically pull-up resistor configurations. **b)** Develop skills in designing and implementing a control system that integrates On/Off and E-Stop functions. **c)** Demonstrate competence in operating and testing safety-critical systems to ensure reliable emergency shutdowns.

(Continued)

Table 1. Laboratory experiment details, objectives, and competencies matrix *(Continued)*

<table>
<tr><td colspan="2">Experiment No. 3
Relevance to Professional Field: Ultrasonic distance sensors enable LED lighting in manufacturing plants to mimic proximity-based systems, saving energy by activating lights only when objects, like robotic arms in automated storage, are nearby.
Laboratory Class Experiment Equivalent: A combination of Arduino control, ultrasonic distance sensing, and Pulse Width Modulation (PWM) features for LED lighting.</td></tr>
<tr><th>Experiment Objectives</th><th>Target Competencies</th></tr>
<tr><td>1. Design a system that activates LEDs based on the proximity of objects, mimicking energy-saving mechanisms in automated storage.
2. Measure and document the accuracy and range of the ultrasonic sensor in detecting various objects.</td><td>a) Gain proficiency in setting up and calibrating ultrasonic distance sensors.
b) Develop skills in integrating sensors with output devices (LEDs) for automated control and implement energy-saving principles.
c) Build competence in analyzing sensor data to evaluate system performance.</td></tr>
<tr><td colspan="2">Experiment No. 4
Relevance to Professional Field: PIR sensor-based stepper motor movement enables dynamic manufacturing plant security monitoring, replicating automated intrusion tracking systems.
Laboratory Class Experiment Equivalent: A combination of Arduino control, PIR sensor, and stepper motor control.</td></tr>
<tr><th>Experiment Objectives</th><th>Target Competencies</th></tr>
<tr><td>1. Implement a stepper motor movement system triggered by PIR sensor detection to mimic automated security monitoring.
2. Test the system's ability to respond dynamically to detected intrusions with precise motor movements.</td><td>a) Gain proficiency in setting up and calibrating PIR sensors for motion detection.
b) Develop skills in controlling stepper motors for precise movements in response to sensor inputs.
c) Build competence in integrating sensors with actuators for dynamic systems.</td></tr>
<tr><td colspan="2">Experiment No. 5,
Relevance to Professional Field: Stepper motor control using a Sharp IR sensor enables precise manufacturing robotics by simulating accurate robotic arm positioning based on workpiece distance in automated assembly.
Laboratory Class Experiment Equivalent: A combination of Arduino control, a sophisticated proximity distance sensor, and stepper motor control.</td></tr>
<tr><th>Experiment Objectives</th><th>Target Competencies</th></tr>
<tr><td>1. Implement a stepper motor control system based on SHARP IR sensor data to mirror accurate robotic arm positioning.
2. Test and verify the system's ability to achieve precise motor movements based on workpiece distance.</td><td>a) Gain proficiency in calibrating Sharp IR sensors for accurate distance measurement.
b) Develop skills in programming and controlling stepper motors for precise positioning.
c) Build competence in integrating sensors with motors for automated control systems.</td></tr>
</table>

Correspondingly, student performance is measured through group scoring, which is assessed based on Experiments 1–3, comparing simulation versus actual results. Experiments 4 and 5 serve as activities for evaluating students' acceptance of the lab equipment's aesthetics, features, and functionality.

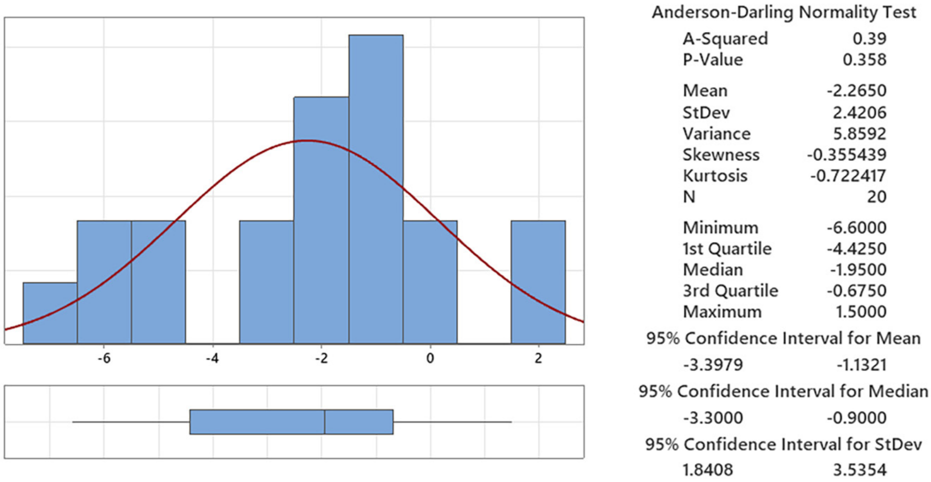
4.5 Evaluation

The objectives and competencies of the experiment activity are measured through the outcomes-based rubric, which implements the following weights: 30% for technical competence, 30% for problem-solving and critical thinking, 20% for collaboration and teamwork, and 20% for communication and documentation. Each rubric weight is then scored according to the following categories: Exemplary (85–100), Proficient (70–84), Developing (50–69), and Beginning (1–49). Additionally, the rubric weights and scoring assessment matrix are shown in Table 2.

Table 2. Matrix of rubric and corresponding score assessment category

Rubric Weights	Scoring Assessment			
	Exemplary (85–100)	Proficient (70–84)	Developing (50–69)	Beginning (1–49)
Technical Competence (30%)	Demonstrates a comprehensive grasp of microcontroller architecture, seamless circuitry design, and component assembly, showcasing precise control and signal configuration, accurate electrical analysis, and tool-validated parameter measurements and calculations.	Display a strong understanding of microcontroller architecture, functional circuitry design, and component assembly with minor flaws, mostly precise control and signal setup, and dependability but with slight inaccuracies or inefficiencies in electrical analysis and tool-validated parameter measurements and calculations.	Shows a basic knowledge of microcontroller architecture, incomplete or inconsistent circuitry design and assembly, partially accurate control and signal setup, incomplete or inconsistent electrical analysis, and tool-validated parameter measurements and calculations.	Lacks knowledge of microcontroller architecture, non-functional or defective circuitry design and assembly, incorrect control signal setup, and minimal or erroneous electrical analysis and tool-validated parameter measurements and calculations.
Problem-Solving and Critical Thinking (30%)	Systematically identifies and resolves all issues in code, circuit, or power measurements with innovative solutions.	Identifies and resolves most issues in code, circuit, or measurements with effective, though not always optimal, solutions.	Identifies some issues but struggles to resolve them fully, resulting in partial functionality.	Fails to identify or resolve issues, leading to nonfunctional or severely limited system performance.
Collaboration and Teamwork (20%)	Exhibits outstanding teamwork, with equitable task distribution and collaboration.	Demonstrates effective teamwork with good collaboration and task sharing.	Shows limited teamwork, with uneven task distribution or collaboration.	Exhibits poor teamwork, with minimal collaboration or contribution.
Communication and Documentation (20%)	Provides clear, detailed documentation (code comments, schematics, power analysis) that is well-organized and reproducible.	Provides adequate documentation that is clear but may have minor gaps in detail or organization.	Provides unclear documentation with significant gaps in code comments, schematics, or analysis.	Produces minimal or no documentation, lacking code comments, schematics, or analysis.

Moreover, the rubric was used to assess the simulation-based and actual lab activities dedicated to Experiments 1–3. For data analysis, Minitab was utilized as the statistical software. Variables (Diffexp1–3) were computed as the difference between simulation scores (S) and actual lab scores (A) (S_n–A_n, where n is the experiment number = [1, 2, 3]). The samples for this analysis were the group scores derived from a total of 20 groups formed in this study, where each group consisted of 5 to 6 students. The graphical summary function in Minitab was employed to reveal the descriptive information of the data, as shown in Figures 3, 4, and 5, including a normality test using the Anderson-Darling Normality Test (H_0: > 0.05, Normal; H_1: ≤ 0.05, Non-normal).



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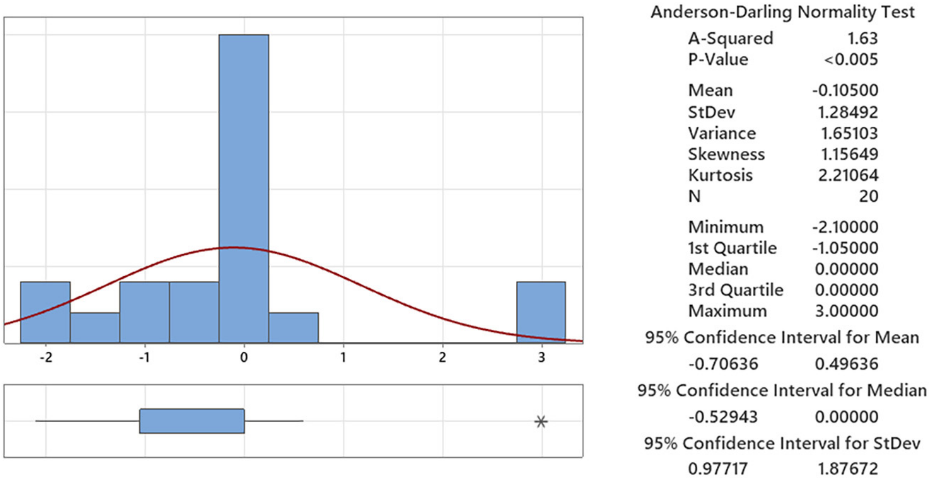
Anderson-Darling Normality Test
  A-Squared            0.39
  P-Value             0.358

  Mean              -2.2650
  StDev              2.4206
  Variance           5.8592
  Skewness        -0.355439
  Kurtosis        -0.722417
  N                      20

  Minimum           -6.6000
  1st Quartile      -4.4250
  Median            -1.9500
  3rd Quartile      -0.6750
  Maximum            1.5000
95% Confidence Interval for Mean
  -3.3979           -1.1321
95% Confidence Interval for Median
  -3.3000           -0.9000
95% Confidence Interval for StDev
  1.8408             3.5354
```

Fig. 3. Minitab graphical summary of differ1



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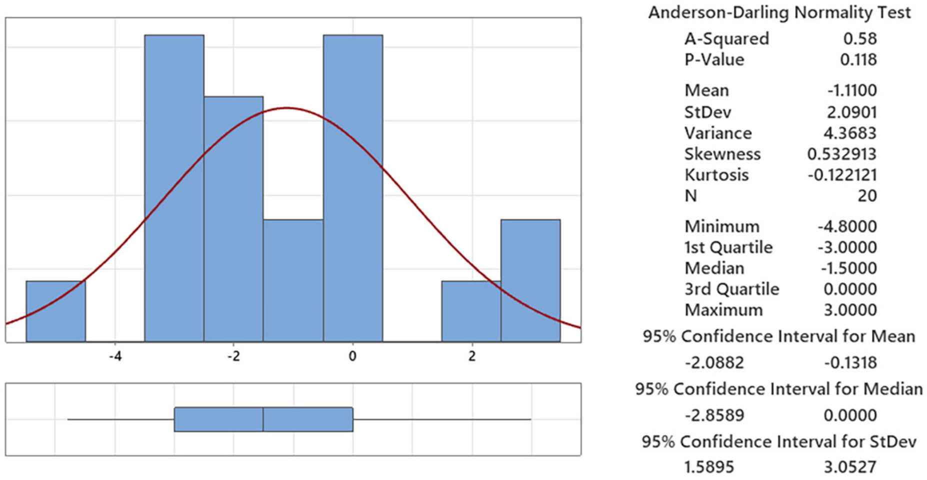
Anderson-Darling Normality Test
  A-Squared            1.63
  P-Value            <0.005

  Mean             -0.10500
  StDev             1.28492
  Variance          1.65103
  Skewness          1.15649
  Kurtosis          2.21064
  N                      20

  Minimum          -2.10000
  1st Quartile     -1.05000
  Median            0.00000
  3rd Quartile      0.00000
  Maximum           3.00000
95% Confidence Interval for Mean
  -0.70636          0.49636
95% Confidence Interval for Median
  -0.52943          0.00000
95% Confidence Interval for StDev
  0.97717           1.87672
```

Fig. 4. Minitab graphical summary of differ2



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Anderson-Darling Normality Test
  A-Squared            0.58
  P-Value             0.118

  Mean              -1.1100
  StDev              2.0901
  Variance           4.3683
  Skewness         0.532913
  Kurtosis        -0.122121
  N                      20

  Minimum           -4.8000
  1st Quartile      -3.0000
  Median            -1.5000
  3rd Quartile       0.0000
  Maximum            3.0000
95% Confidence Interval for Mean
  -2.0882           -0.1318
95% Confidence Interval for Median
  -2.8589            0.0000
95% Confidence Interval for StDev
  1.5895             3.0527
```

Fig. 5. Minitab graphical summary of differ3

Furthermore, a Grubbs's outlier test (H_0: > 0.05, without outlier; H_1: ≤ 0.05, with outlier) was conducted to confirm the presence of any extreme data points. The selection of appropriate statistical methods depends on the satisfaction of their corresponding assumptions. The best-suited statistical methods employed were the one-sample T-test (for Experiments 1 and 3) and the One-sample Sign Test (for Experiment 2). Assumptions for conducting both the One-sample T-test and one-sample sign test were met. Although not all of the 20 groups achieved significant improvement based on their raw scores, Table 3 ultimately reveals that students improved their performance using the developed lab equipment across the first three experiments/activities when comparing simulation-based versus actual lab-based results.

Table 3. Data analysis for experiments 1–3

Variable	n	Normality Test (H_0 = Normal, H_1 = Non-Normal	Outliers Test (H_0 = No Outlier, H_1 = With Outlier) [Min, Max, G, P-Value, Remarks]	Hypothesis and Statistical Method	P-Value and Remarks
Diffexp1 = $S_1 - A_1$	20	P = 0.358 (normal)	–6.6, 1.5, 1.79, 1.0, no outlier	H_0: $\mu = 0$ H_1: $\mu < 0$ One Sample T-test	0.0002 Improved
Diffexp2 = $S_2 - A_2$	20	P = <0.005 (non-normal)	–2.1, 3.0, 2.42, 0.177, no outlier	H_0: $\eta = 0$ H_1: $\eta < 0$ One Sample Sign Test	0.0006 Improved
Diffexp3 = $S_3 - A_3$	20	P = 0.118 (normal)	–4.8, 3.0, 1.97, 0.797, no outlier	H_0: $\mu = 0$ H_1: $\mu < 0$ One Sample T-test	0.0141 Improved

For Experiments 4 and 5, the effectiveness of the developed lab equipment was evaluated through a mixed-methods approach, combining quantitative analysis using Likert scales and qualitative analysis via Braun and Clarke's 6-Step Thematic Analysis [41]. For the quantitative component, specifically the Likert items, reliability of the survey was assessed using Cronbach's alpha, with Minitab employed for the analysis. Among the 100 students enrolled, 77 responded to the survey. Table 4 presents the Likert items' respective means, standard deviations, and Cronbach's alpha values. The Likert items demonstrate strong reliability, as all Cronbach's alpha values exceed 0.90.

Table 4. Data analysis for quantitative data in the mixed-method approach

Likert Items	Mean	St. Dev.	Cronbach's Alpha	Interpretation
1. Prototype Functionality				
1.1. The equipment was easy to set up and get started with.	4.325	0.595	0.9226	Strongly Agree
1.2. The controls were intuitive and user-friendly, making it easy to learn.	4.390	0.610	0.9193	Strongly Agree
1.3. I found it easy to precisely control the stepper motor's movements.	4.312	0.634	0.9221	Strongly Agree
1.4. The stepper motor consistently achieved the desired positions with accuracy.	4.338	0.641	0.9224	Strongly Agree
1.5. The sensors onboard functioned reliably and as expected.	4.481	0.576	0.9184	Strongly Agree
1.6. The equipment operated consistently throughout my testing without any malfunctions or errors.	4.519	0.576	0.9214	Strongly Agree
1.7. I felt confident in the overall stability and reliability of the prototype.	4.429	0.658	0.9185	Strongly Agree

(Continued)

Table 4. Data analysis for quantitative data in the mixed-method approach *(Continued)*

Likert Items	Mean	St. Dev.	Cronbach's Alpha	Interpretation
2. Acceptability and Suitability				
2.1. This equipment would be useful for my typical laboratory work and experiments.	4.623	0.563	0.9234	Strongly Agree
2.2. The prototype offers advantages over similar laboratory equipment I have used in the past.	4.481	0.681	0.9240	Strongly Agree
2.3. I would consider replacing my current equipment with this prototype if it were available.	4.351	0.757	0.9210	Strongly Agree
3. Aesthetics, Design, and Safety				
3.1. The prototype has a visually appealing and modern design.	4.325	0.637	0.9229	Strongly Agree
3.2. The equipment is comfortable and easy to use for extended periods without causing strain.	4.351	0.623	0.9185	Strongly Agree
3.3. The prototype appears to be durable, well-constructed, and made of quality materials.	4.416	0.676	0.9205	Strongly Agree
3.4. I feel safe operating this equipment and believe it is designed with user safety in mind.	4.532	0.575	0.9205	Strongly Agree
4. Overall Satisfaction				
4.1. How satisfied are you with the overall performance of the prototype?	4.610	0.588	0.9229	Very Satisfied

Moreover, the Likert scale, its score intervals, and interpretation are consistent with the instrument utilized in the study by Nyutu et al. (2020) [42]. The survey's interpretation features five categories: Strongly Agree/Very Satisfied (4.21–5.00), Agree/Satisfied (3.41–4.20), Neutral (2.61–3.40), Disagree/Dissatisfied (1.81–2.60), and Strongly Disagree/Very Dissatisfied (1.00–1.80). This study reveals that students strongly agree with the functionality, suitability, aesthetics, design, and safety of the laboratory equipment developed. This positive feedback also correlates with their improved scores in actual lab experiments compared to simulations.

Table 5. Qualitative analysis using Braun and Clarke's 6-step thematic analysis in the mix-method approach

Q1 Theme	f	Q2 Theme	f	Q3 Theme	f
User-Friendliness	15	Usability and Interface Challenges	5	Usability and User Experience	8
Performance and Efficiency	12	Performance and Responsiveness	3	Performance and Stability	4
Aesthetics and Design	7	Physical Design, Aesthetics, Durability, and Maintenance	9	Physical Design and Durability	9
Component-Specific Features	20	Functionality and Feature Limitations	5	Functionality and Features	7
Reliability and Stability	8	Cable Management	3	Total	28
Educational Value	7	Sensor-Related Issues	3		
Total	69	Customization and Scalability	3		
		Total	31		

Notes: Q1 – What are the strongest features of the prototype that contribute most to your satisfaction?;
Q2 – What are the weakest features of the prototype that you think need improvement?;
Q3 – What overall improvements or modifications would you suggest for the prototype?

The Braun and Clarke's 6-Step Thematic Analysis includes the process of familiarization with the data, coding, searching for themes, reviewing themes, defining and naming themes, and writing up [41]. Table 5 summarizes the results of the qualitative analysis extracted from the three questions (Q1 to Q3). Additionally, irrelevant or vague responses were identified, totaling 10 for Q1, 46 for Q2, and 49 for Q3. Common examples included "none," "N/A," and ".". These responses were not included in Table 5.

For Q1, the most common occurring theme was "Component-Specific Features," which received 20 mentions, with examples such as: "The ultrasonic sensor and motion sensor because it is accurate and it works properly," "Stepper Motor because it can be used in 3D Printing," and "The Sharp IR Sensor." This was followed by "User-Friendliness" as the second most common theme, with examples including: "It is working properly, plus it is easy and pretty convenient to use," "It's user-friendly, it's so easy to use. The parts don't seem complicated," and "Easy to navigate buttons." Third, for "Performance and Efficiency," some responses are: "Functionality and Speed," "Performance efficiency," and "Satisfied with how simple, reliable, and quick the prototype is to use." Overall, Q1 garnered 69 substantial responses, with some comments contributing to multiple themes.

For Q2, "Physical Design, Aesthetics, Durability, and Maintenance" was the most frequently identified theme with nine mentions, with responses such as: "I think the little bit weakest feature is the casing is slightly compact, I think better have more space," "The only concern for this type of machine is the cost for maintenance if some outsource parts are required," and "Durability and maintenance." This was followed by "Usability and Interface Challenges," which received five mentions, with examples including: "The interface could be improved for easier operation and better user experience," "Complexity in Setup," and "Aside with its appearance that makes it look like hard to understand, it all perfect for me." Tied with five mentions, the "Functionality and Feature Limitations" theme included responses such as: "The weakest features of the prototype may include limited functionality," "Limited function," and "Incomplete Functionality- when certain features are limited or don't work as expected."

For Q3, "Physical Design and Durability" received the highest number of mentions with 9, with answers such as: "The prototype casing, better more spacing," "The base material must be not fragile," and "Better container or body for the components for the stepper motor." This was followed by "Usability and User Experience" with eight mentions, with responses such as: "Streamline the layout to make it cleaner and more intuitive, removing any unnecessary elements," "Simplify navigation for a more intuitive user experience," and "Making a guide on how to use its different functions would be a great addition." Finally, "Functionality and Features," as the third most common with seven mentions, included: "Expand core functionality: Based on user needs, consider adding features," "Include a buzzer that sounds an alert when motion is detected," and "Make it to differentiate the things using sensors."

In synthesis, a comparative quantitative analysis of Experiments 1 to 3 revealed an improvement in student performance during laboratory activities conducted in an actual setup. Free applications such as Tinkercad cannot simulate stepper motors. The evaluation of actual stepper motor activity employed a mixed-methods approach. Quantitatively, a 5-point Likert scale survey was utilized, and its reliability was assessed through item analysis using Cronbach's Alpha. Qualitatively, Braun & Clarke's 6-Step Thematic Analysis was applied. Accordingly, the four categories of Likert items: Prototype Functionality, Acceptability and Suitability, Aesthetics, Design, and Safety, and Overall Satisfaction received "strongly agree" or "very satisfied" remarks in the survey results. This aligns with the thematic analysis, which also described strong features of the developed lab equipment. Moreover, the qualitative findings also acknowledge weaknesses and suggestions primarily concerning the prototype's compact design, maintenance, interface complexity, and limited functionality. Responses indicate that the compact casing, while noted for future design iterations, is essential to the equipment's portability. Maintenance cost concerns will be addressed by requesting components in advance or suggesting university stockpiling, though material durability is defended as meticulously selected. Interface complexity and unclear appearance will be mitigated through demonstrations at the start of the semester to explain components and operation. Furthermore, suggestions for user guides and simplified navigation will also be handled through demonstrations. Lastly, concerns and suggestions regarding limited functionality, additional features such as buzzers or sensors, and layout streamlining are acknowledged as valuable inputs for the next design and reproduction.

5 STUDY LIMITATIONS

While this study offers insights and evidently compares simulation versus in-person microcontroller lab learning, several limitations are acknowledged. First, the sample was restricted to 100 third-year students, which was then grouped into 20 samples only from two academic sections, limiting statistical power for subgroup analyses and generalizability to broader student populations, such as similar engineering fields or even institutions. Second, direct simulation-to-actual comparisons were possible for just three basic-to-intermediate Arduino experiments 1–3 only. Critically, the stepper motor experiments could not be compared due to Tinkercad's lack of simulation capabilities for these components. Instead, stepper motor activities were evaluated solely through student perceptions via mixed methods (Cronbach's alpha reliability and thematic analysis). While this revealed subjective feedback, it failed to measure objectives and technical competencies, leaving the efficacy of physical stepper lab equipment indirectly inferred. Finally, the hardware-specific design of the stepper lab setup may limit reproducibility across institutions with different lab equipment.

6 FUTURE RESEARCH DIRECTIONS

Based on these findings, several key directions for future research are apparent. First, to address the absence of direct comparisons between simulation and physical lab activities in Experiments 4 and 5, it is suggested to explore other free online simulation applications with stepper components, such as Wokwi, or subscription software, such as Proteus and Multisim, to facilitate performance comparisons. Second, expand and integrate IoT modules such as ESP32 Wi-Fi/Bluetooth into the physical stepper lab equipment, enabling remote monitoring of sensor data from ultrasonic, PIR, and IR sensors and motor control. This allows studies on IoT-enhanced pedagogy. Third, enhance the lab equipment further [7] by integrating other types of motors, such as DC motors and servo motors, enabling students to learn and operate diverse motor types, thereby fostering a higher level of technical competence. Fourth, design experiments measuring troubleshooting speed, circuit efficiency, or code accuracy for stepper systems to quantify learning efficacy and expand objective skill assessments.

Fifth, scale implementation across related technology-based departments in engineering, such as mechatronics, electronics, electrical, computer, and mechanical engineering, and student cohorts like multi-institution collaborations to evaluate cross-disciplinary adaptability and resource constraints. Sixth, develop hybrid lab models that integrate virtual simulations for practicing theoretical and complex concepts with physical hardware sessions for hands-on skill assessment [9], thereby maximizing learning outcomes and fostering a comprehensive understanding of stepper motor applications. Finally, explore AI-driven adaptive learning tools that personalize lab tasks based on student performance data from both modalities, potentially closing skill gaps.

7 CONCLUSION

The development and implementation of the Stepper Motor Engineering Lab have successfully addressed the need for enhanced hands-on learning in the Manufacturing Engineering program, integrating basic and intermediate applications of microcontrollers. The lab setup provides students with a robust platform to explore simple logic control, automation, and robotics. The results from the five designed experiments demonstrate significant improvements in student performance when using physical lab equipment compared to simulation-based methods, particularly in Experiments 1–3, as evidenced by statistical analyses using Minitab. The mixed-methods evaluation of Experiments 4 and 5 further confirms the effectiveness of the developed lab, with Likert scale surveys indicating strong student satisfaction across functionality, aesthetics, design, safety, and overall suitability, which is supported by high Cronbach's alpha reliability scores (>0.90). Qualitative insights from Braun and Clarke's 6-Step Thematic Analysis highlight the lab's user-friendliness, component-specific features, and performance efficiency as key strengths, while identifying minor areas for improvement, such as compactness of physical design and usability enhancements. These findings align with stakeholder concerns raised during the last meeting, emphasizing the need for practical, industry-relevant laboratory equipment to complement simulation activities. By integrating advanced sensors, durable materials, and flexible setups such as breadboarding, the lab equips students with the technical competence, problem-solving skills, and collaborative abilities required for modern manufacturing environments. Future iterations of the lab could address suggested improvements, such as enhanced casing design and streamlined interfaces, to further optimize the learning experience.

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