MEKATRONIKA: JOURNAL OF INTELLIGENT MANUFACTURING AND MECHATRONICS
E-ISSN: 2637-0883
VOLUME 8, ISSUE 2, 2026, In-Press
DOI: https://doi.org/10.15282/mekatronika.v8i2.13889

RESEARCH ARTICLE

Enhancing competencies in instrumentation and measurement through project-based learning: A case study of an automated car reversing system

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Abstract: Necessary in today's engineering programs. The present study provides an example of how project-based learning (PBL) was implemented in the Instrumentation and Measurement course, MECH 2241, by developing an Automated Car Reversing System with Emergency Brake. In developing this project, students demonstrated their ability to utilize all the course outcomes related to sensors, actuators, signal conditioning, and performance evaluation of a system through the integration of sensing, signal conditioning, embedded programming, and control logic. Students utilized an Arduino Mega, an HC-SR04 ultrasonic sensor, a buzzer, a motor driver, and a DC motor to build a prototype that provided an audible warning and ultimately stopped the motor if an obstruction was found, within 20 centimeters. Experimental research demonstrated that the prototype, after calibration according to the 97.25% average accuracy (y = 0.0172x + 0.8377), achieved the course outcomes stated above. Additionally, a results-based questionnaire was administered to assess the students' opinion of the PBL project, with 91.1% of the 45 respondents agreeing or strongly agreeing that they gained a better appreciation for the relationship between measurement theory and engineering practice through this hands-on projected. PBL has positively impacted the students' technical knowledge of instrumentation and measurement and has increased their engagement in and relationship with higher education institutions.

Article History
Received : 24 January 2026
Revised : 23 April 2026
Accepted : 6 September 2026
Published : 30 October 2026

Keywords
Project-based learning
Instrumentation and measurement
Active control
Ultrasonic sensor
Engineering education

1. Introduction

Modern engineering education requires a transition from theoretical knowledge to practical application [1–3]. At the Kulliyyah of Engineering, International Islamic University Malaysia, the MECH 2241 Instrumentation and Measurement course utilizes Project-Based Learning (PBL) to bridge this gap. This article discusses the design and implementation of an "Arduino Reversed Car Sensor System" as a vehicle for achieving complex engineering problem-solving (PO2) and design solutions (PO3). The project specifically addresses the core course outcomes: explaining sensor principles (CLO1), selecting suitable actuators (CLO2), designing signal logic (CLO3), and evaluating system performance (CLO4). In literature, the relevance of problem-based learning (PBL) is firmly established. Studies indicate that PBL promotes enhanced "knowledge correlation", where learners use electrical measurement and mechatronics to apply learned theory in developing new, functional systems [4–6]. By engaging in a products-based assignment, students demonstrate critical skills for success in 21st century workforce which includes teamwork, self-directed learning and the ability to persist in frustrating cycles during hardware debugging processes [7].

This study discusses the implementation of an "Arduino Reversed Car Sensor System with Emergency Braking" as a vehicle for achieving both technical and professional competencies. The project was designed to address four specific Course Learning Outcomes (CLOs):

- CLO1: Explaining basic principle of instrumentation, measurement and sensors technology
- CLO2: Select suitable sensors and actuators for target applications.
- CLO3: Apply fundamental methods to design signal conditioning circuits for target application (analog and digital).
- CLO4: Evaluate the performance of the instrumentation systems.

The project is divided into two tracks which are software and hardware track. The project presented in this study which is "Arduino Reversed Car Sensor System with Emergency Braking" is under the *Hardware Track.* It requires students to use of microcontrollers (e.g., ESP32 or Arduino) and real-time sensor feedback to solve a design challenge [8]. The project also meets some of the curricular requirements for 'Engineering Knowledge' (PO1) and 'Problem Analysis' (PO2) as it will require students to provide justification for their design choices, such as using ultrasonic sensors for obstacle avoidance, through a systematic evaluation and calibration of the designs.

This project emulates the specifications of vehicles manufactured in the auto industry today. All vehicles should contain reverse sensor systems. Sensors generate audible sound when an object is detected within its predetermined range of distance. The sensor system is essential for assisting drivers with the detection of obstacles or objects behind their vehicle that is in the blind spot not visible with the direct line of sight. As such, this technology has the potential to stop crashes from occurring when backing up a vehicle [9,10]. However, while most vehicles are equipped with reverse sensors

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that provide audible warnings, it still needs to rely entirely on the driver's reaction time to apply the brakes. Collisions with obstructing objects occur frequently because of driver distraction or delayed reflexes in responding to alert signals. As such, development of an active system to automatically reduce the power or even stop the motor prior to having an accident have been identified as an effective method to reduce human error.

This project was not only about building a prototype, but it also provided an opportunity for students to experience and learn how to implement Project-Based Learning (PBL) as they attempted to better understand the complicated concepts of instrumentation and measurement through a practical approach. Based on the limitation of passive warning systems, students were asked to change their focus from simple detection to develop an Active Control and Obstacle Avoidance. This change gave rise to a deep investigation of the instrumentation chain, which included examining how to sense using different types of technology and understanding the physics of how those sensors were able to sense their environment, both stationary and non-stationary. Additionally, students need to consider how to make the necessary changes that would allow the real time sensor data to be used to counter undesirable system behavior and significantly reduce the potential for human error through automatic braking.

The primary goal of this project, and the purpose of this article, is to illustrate how the design of an "Arduino-Based Reversed Car Sensors System" can assist in a full understanding of the instrumentation life cycle. Students learn practical applications of the following concepts by working on the hardware track. The project will be completed by going from theoretical definitions of the hardware to a working knowledge of:

- Sensor Characterization. Understanding how ultrasonic transducers work which includes the operational characteristics and physical limitations.
- Actuator Integration. Connecting digital logic with physical mechanical motion using motor driver circuits.
- System Evaluation. Using empirical methods to calibrate and test reliability of an integrated measurement system.

Finally, this case study highlights how PBL transforms the classroom into a practical laboratory for complex engineering problem-solving.

2. Materials and Methods

The methodology was developed based on a professional engineering design process, which transitions from theoretical selection to empirical validation. As a result, the students are not simply "building" a solution, but they are "engineering" a solution based on the course learning outcomes provided.

2.1 Project Design and Component Selection (CLO1 & CLO2)

The visual design required for the *Hardware Track* asked students to use microcontrollers to solve a design problem when designing their "Complex Engineering Problem (CEP)" dealing with automotive safety features.

Sensing Principle

Each student provided an explanation of how the HC-SR04 ultrasonic sensor works and explained that the sensor emits a 40 kHz ultrasonic pulse and measures the "Time of Flight"(ToF) of the echo returning to determine distance. This clearly aligns with the learning outcome (CLO1), understanding how sensor technology works.

Actuation Logic

Braking system simulation required L298N DC motor driver integration. The selection process required students to justify how digital signals from the Arduino Mega could control high-current DC motors, fulfilling CLO2 (selecting suitable actuators). Figure 1 shows the automated car reversing experimental setup created by students. It consists of an ultrasonic sensor mounted to the back of the prototype car for measuring the distance from the car to the object it will collide with. This measured distance is sent to Arduino Mega, which acts as the system's primary controller. An appropriate signal will then be sent from the Arduino to the motor driver based on the calibrated distance value. The motor driver will then control the operation of the DC motor for the car, either allowing the vehicle to continue to move backward or stopping the motor when the object reaches the critical braking distance. The complete instrumentation system therefore demonstrates the integration of sensors, signal processing, control logic and actuation.

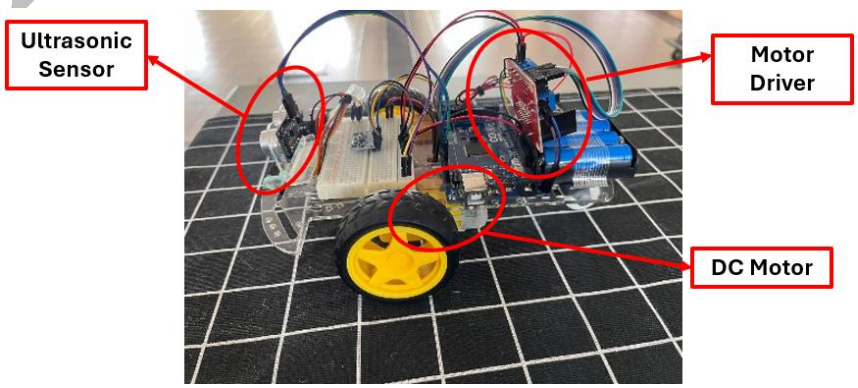


Figure 1. Hardware setup

2.2 System Architecture and Signal Logic (CLO3)

The instrumentation task's main focus was determining the logic needed for signal conditioning and system response. As specified in the project instruction which is to "integrate real time sensor feedback", a tiered logic strategy for providing an alert signal was developed. The flowchart for the logic system is outlined in Figure 2. A summary of the major process steps is provided below.

- Safety Zone (> 45 cm). This zone did not require any intervention by the system, and the motors would perform as expected.
- Warning Zone (45 cm – 20 cm). When the vehicle approaches a tracked object in the warning zone, the signal conditioning logic will produce an audible alert through a tone modulated by frequency. As the vehicle gets closer to the tracked object, the interval between buzzer sounds decreases from 0.6 sec to 0.2 sec. These intervals provide nonlinear warning signals to warn the operator.
- Critical Zone (< 20 cm). When a tracked object is less than 20 cm from the back of the vehicle, the system will provide active control intervention. The Arduino will send a low signal to the motor driver stopping the rear wheels of the vehicle while maintaining a constant tone from the buzzer.

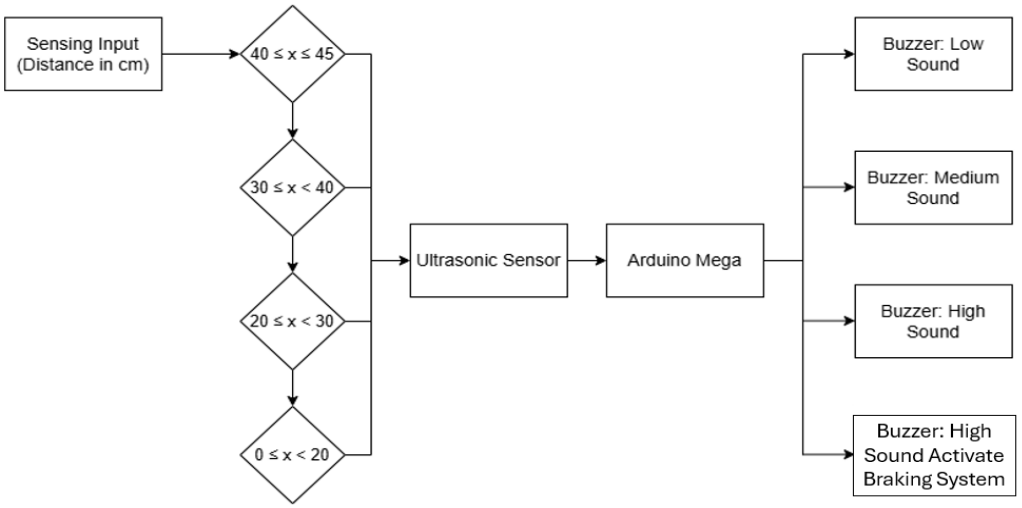


Figure 2. Block diagram

```
BEGIN

Initialize ultrasonic sensor, buzzer, motor driver and serial monitor
Set motor speed and initial motor condition

REPEAT continuously

    Acquire ultrasonic echo signal

    IF echo signal is valid THEN
        Convert echo time into distance
        Apply calibration equation to obtain calibrated distance
    ELSE
        Mark distance as invalid
    END IF
    IF calibrated distance > 45 cm OR distance is invalid THEN
        Turn buzzer OFF
        Move motor backward
    ELSE IF calibrated distance is between 40 cm and 45 cm THEN
        Activate slow intermittent buzzer
        Move motor backward
    ELSE IF calibrated distance is between 30 cm and 40 cm THEN
        Activate medium intermittent buzzer
        Move motor backward
    ELSE IF calibrated distance is between 20 cm and 30 cm THEN
        Activate fast intermittent buzzer
        Move motor backward
    ELSE IF calibrated distance ≤ 20 cm THEN
        Activate continuous buzzer
        Stop motor immediately
    END IF

END REPEAT
END
```

Figure 3. Pseudocode of the implemented code

To achieve the functions described above, the Arduino Mega was programmed in C++ using the Arduino IDE. Students organized the control algorithm of the system to classify measured distances into the categories of safety zone, warning zone, and critical zone using an if-else conditional structure and developed different buzzer signals and motor-control commands for each range of distance. The HC-SR04 ultrasonic sensor was activated periodically to read echo time, convert the echo time to distance, and compare the distance to the corresponding threshold values. The timing of the buzzer was accomplished using a non-blocking timing method (based on the *millis( )* function) so that the Arduino could keep checking the ultrasonic sensor and updating the motor driver output while generating the tiered audio warning. Through the completion of the C++ programming exercise, the students developed an understanding of how real-time feedback through sensors, control of timing, and control of actuators are incorporated into an embedded instrumentation system. Figure 3 provides pseudocode for the code that the students used in the implementation.

Table 1 presents the distance-based control algorithm and parameter settings implemented in the project. The table also provides troubleshooting checklist to verify whether the buzzer and motor responses operate correctly at each distance range.

Table 1. Tiered control algorithm and parameter settings for buzzer and motor response based on obstacle distance

Distance range	System condition	Buzzer response	Motor response
> 45 cm	Safe zone	OFF	Motor ON
30–45 cm	Low warning	Slow intermittent beep	Motor ON
20–30 cm	High warning	Fast intermittent beep	Motor ON
< 20 cm	Critical zone	Continuous tone	Motor STOP

2.3 Experimental Calibration and Performance Evaluation (LO4)

One of the major components outlined in the MECH 2241 course outline states that a formal section on "Calibration and Data Analysis" must be included in the projects. Students conducted controlled tests using a flat surface for an obstacle. The results were then compared using a measuring device (i.e., a ruler) on a 5 cm basis of measurement to measure how far the signal from the sensor was from the measuring device. All data collected would serve as a basis for future signal conditioning purposes. The signal conditioning method for this project used software on an Arduino Mega board as the medium of processing signals. The echo duration in microseconds (i.e., duration of echo from an object) produced by the HC-SR04 sensor was used to determine the Time-of-Flight (ToF) value that would be converted into the distance travelled by the echo using the speed of sound constant, 0.0343 cm/μs. The time duration signal (t) recorded by the microcontroller is then converted to signal (d) by using the stated constant based upon the sound distance travelled.

$$d = \frac{t \times 0.0343}{2} \tag{1}$$

Average of multiple readings was calculated before using them for calibration and threshold comparison in order to minimize the impact of random variability in data readings. Once calibrated, the systematic error of the sensor due to sensor timing delays, internal processing delays, and practical limitations of measurement were also adjusted. This is conducted to use the corrected version of echo time in the control logic for decision making at the tiered warning and emergency braking levels. This work was completed to assess the performance of the system as required by CLO4. In addition, ten trials at the critical threshold level of 20 cm were performed to evaluate system precision and mean accuracy.

2.4 Mapping to Course Outcomes and Students' Satisfaction Analysis

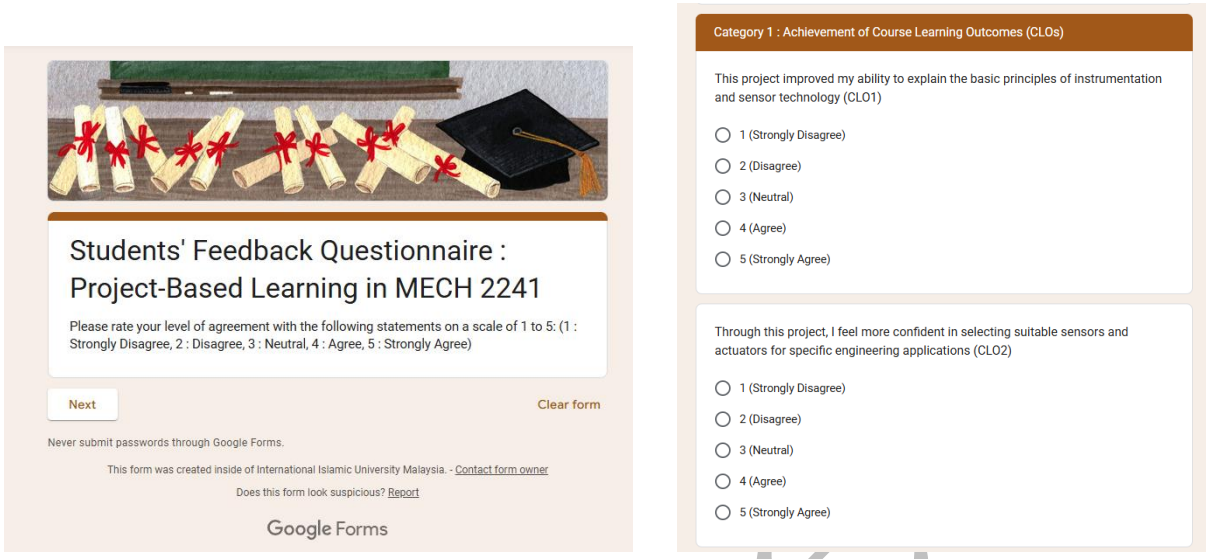
In terms of course outcomes and student satisfaction analysis, the methodology applied to this project was explicitly mapped to the Malaysian Qualification Framework (MQF) Level 6 requirements. By requiring students to document these steps, the PBL framework ensured they applied "Engineering Knowledge" (PO1) and "Design of Solutions" (PO3) to a safety-critical application, transforming a classroom exercise into an industry-relevant experience. From an integration perspective of the project, it addresses all three program outcomes at a high level. The project supports PO1 through the application of engineering principles and concepts learned in engineering fundamentals. The project also supports the PO2 through tasks that require the student to analyse measurement error, sensor limitations, and system response to various distance thresholds. The project also supports PO3 because the student is creating a working solution that integrates sensors, signal conditioning, control logic, and actuation to solve a safety-related design requirement. Consequently, the use of PBL activities has provided a means to quantify course outcomes as technical assessments.

In addition to the technical assessment, a questionnaire via Google Forms as shown in Figure 4 was used to evaluate student perceptions on the implementation of Project Based Learning (PBL) into solving engineering problems. After completion of the project, students completed the questionnaire, to measure how well they achieved course learning outcomes and to measure how well students developed technical skills and were able to integrate tools into solving engineering problems. The first measurement within the questionnaire was a measurement of improvements by students regarding their ability to explain the principles of sensors, how to select sensors and actuators, how to perform signal conditioning, and how to evaluate the performance of an engineering system. The second area of measurement on the questionnaire was the experience of students in integrating tools such as Arduino, Python, MATLAB, and Simscape, with their sensors and the data acquisition processes associated with their project. The third area of measurement within the questionnaire helped determine whether the completion of a hands-on project increased the experiences and interests of

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students and helped them connect the theoretical concepts they were exposed to in completing their measurements and how those concepts were applied to solve engineering problems through practical engineering applications.

All responses collected through the Google Form were evaluated according to a Likert-type scale from 1 (Strongly Disagree) to 5 (Strongly Agree). Each item on the questionnaire was evaluated based on the percentage of respondents that agreed with the statement. This questionnaire served as the pedagogical evaluation component of the study, complementing the technical evaluation obtained from calibration, validation, and system accuracy analysis.



(a) (b)

Figure 4. Google Form design for the students' satisfaction questionnaire: (a) front page and (2) sample questions for category 1

3. Results and Discussion

Evaluation of the "Arduino Reverse Car Sensor System" consisted of two phases which are systematic calibration for sensor transfer function establishment and validation phase to determine reliable and accurate performance of the Sensor System in critical safety zones.

3.1 Sensor Calibration and Characterization

To satisfy the requirements of performance evaluation (CLO4), students first established the relationship between the raw Time of Flight (ToF) and the physical distance. Data was recorded at 5 cm intervals, as shown in Table 2.

Actual object distance versus the measured distance from the ultrasonic sensor's output relationship was investigated. Three records at each target distance were taken, and an average was calculated to minimize random measurement error. The raw echo time return, in microseconds (µs), was recorded from the sensor to establish the relationship between the time-of-flight and actual distance, as well as a calibration value computed based on the average raw time reading.

"*The relationship between the sensor raw time and the actual measured distance is shown in Figure 5. An increase in the time-of-flight is directly correlated with an increase in the real distance between the sensor and the target, according to the plotted data, which shows a positive linear trend. A proportional relationship between the two variables is confirmed by the linear regression line fitted to the data, y = 0.0172x + 0.8377 which yields an equation with a positive slope value of 0.0172. This behavior is in line with the ultrasonic sensors' working principle, which states that longer wave propagation times occur at greater distances. A slight systematic offset is indicated by the small positive y-intercept (0.8377), which is probably caused by internal processing delays or sensor hardware constraints."*- taken from students' report.

The paragraph written above shows that students can identify the "Complex Engineering Activities" (EA5). This task is important in PBL framework, moving students from simple assembly to deep technical analysis. During presentation, students were asked regarding the 40 cm anomaly, what reason makes this anomaly happened.

"Results from the 40 cm trial demonstrate an outlier in the measured distance readings resulting in lower values than required for the 2nd and 3rd measurements. Eventhough the value is lower, the corresponding raw time-of-flight (TOF) values still fall within the trend of increasing TOF Values and produced the calibrated distance of 39.89 cm. This may indicate that the outliers were due to transient echo instability or readout inconsistency. Hence, this does not indicate a failed sensor. Additionally, it was expected a slightly misaligned obstacle surface, variation in reflected ultrasonic energy off an obstacle, environmental noise, resolution limitations of the sensor, or timing jitter during measurement. This phenomenon shows the evident of uncertainties in real measurement rather than only using ideal data." is the answer from students.

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Table 2. Experimental sensor readings and calibrated distance values for various obstacle thresholds

Actual Distance (cm)	Distance (cm)				Sensor Raw Time (µs)				Calibration (cm)
	1st reading	2nd reading	3rd reading	Average reading (cm)	1st reading	2nd reading	3rd reading	Average reading (µs)	
20.00	19.00	19.00	19.00	19.00	1121.00	1123.00	1120.00	1121.33	20.12
30.00	28.00	28.00	28.00	28.00	1664.00	1667.00	1685.00	1672.00	29.60
40.00	38.00	28.00	28.00	28.00	2287.00	2259.00	2266.00	2270.67	39.89
45.00	44.00	43.00	44.00	43.67	2600.00	2566.00	2597.00	2587.67	45.35
50.00	48.00	47.00	48.00	47.67	2836.00	2837.00	2836.00	2836.33	49.62

*Note: An anomaly was observed during the 40 cm trial, particularly in the measured distance readings.

By observing the answer to the anomaly phenomena, students have fulfilled the requirement of CLO1, "Explain basic principle of instrumentation, measurement and sensors technology." Additionally, the callibration process showed that students have fulfilled CLO3, "Apply fundamental methods to design signal conditioning circuit for target application (analog and digital)".

3.2 System Validation and Accuracy Analysis

The second phase of the results focuses on the system's performance at the 20 cm critical threshold, the point where the emergency braking system (active control) is triggered. The result is shown in Table 3.

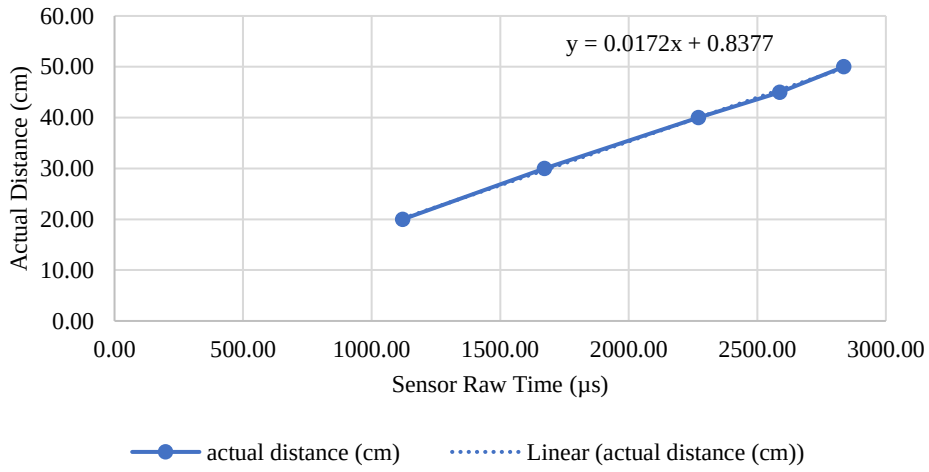


Figure 5. Linear regression analysis of sensor raw time versus actual distance for system calibration

Table 3. Validation of ultrasonic sensor readings for a 20 cm reference distance

Actual distance: 20 cm		
Reading, n	Calculate distance, x_n (in cm)	Deviation, $(d = x_n - \overline{x})$
1	19.33	-0.10
2	19.45	0.02
3	19.45	0.02
4	19.45	0.02
5	19.45	0.02
6	19.45	0.02
7	19.45	0.02
8	19.33	-0.10
9	19.45	0.02
10	19.45	0.02

The system produced a high level of repeatability and precision. 0.9988, in terms of the ten tests run, as demonstrated by the values with maximum deviation from the average of ±0.02 cm. Hence, the overall performance metrics for the tests are shown below.

- Mean Measured Distance: 19.426 cm
- Systematic Error: 2.75%
- Final Accuracy: 97.25%

"*The low spread between repeated samples (19.33–19.45 cm) in the validation data for the 20 cm test point indicates that the ultrasonic sensor readings are very consistent. The sensor appears to have good repeatability based on the small variation. Sensor timing delays and internal processing offsets are probably to blame for the calculated mean value of 19.42 cm, which shows a slight systematic underestimation in relation to the actual distance. The low percentage error (<3%) in spite of this bias shows that the sensor's performance is suitable for short-range distance measurement applications. The percentage error calculated is* 2.75 *%. This makes the percentage accuracy reach 97.25%.",* taken from students' report.

Students did not only complete a numerical calculation, they also analyzed the behavior of the instrumentation chain. Their statements demonstrate that they achieved the transition from Sensing (CLO1), to Conditioning (CLO3), to a final Evaluation (CLO4). Thereby achieving the overall outcome of the MECH 2241 course.

3.3 Pedagogical Discussion: Bridging Theory and Practice

The technical success of the autonomous car braking system directly correlates with the student's mastery of instrumentation concepts. Students' analysis on the sensor performance concluded that the influence of the signal conditioning design was significant in creating a connection between raw incoming data and functional logical (Output) processes. By identifying "internal processing offsets" and "timing delays", students gained an understanding of how digital instrumentation utilizes a specific calibration engineering mathematics equation through the application of a software-based signal conditioning layer. In this case is to produce an equation of $y = 0.0172x + 0.8377$ to transform raw "Time of Flight (ToF)" sensor data into a reasonable distance measurement. This based directly upon the fundamental processes associated with digital signal processing contained within CLO3, as these actions ensure that the input data is linearized and corrected before being provided to the controlled actuating device.

From a pedagogical perspective, the implementation of PBL through the autonomous car braking system enabled students to understand and experience signal conditioning as more than a theoretical circuit concept. There are various physical processes involved such as converting raw sensor timing data to a reasonable representation of distance through correcting the distance through calibration and utilizing the corrected data to control in real-time. Additionally, the incorporation of calibrated sensing devices, non-blocking buzzer or use of half-duplex timing, and motor to control object provided students with a complete understanding of the measurement acquisition to actuator response instrumentation chain.

Furthermore, students analysed that the "tiered alert logic" design is fully dependent on the accuracy of the conditioned signal. Observation on sensor "bias" by the students indicates that they recognize the need to consider the physical limitations of actual hardware when designing a logical device, so it will function reliably. In the case of a safety-critical application such as a braking system, which will trigger at an approximate distance of less than 20 cm, the signal conditioning stage is responsible for ensuring that the alert intervals (buzzer activation) trigger properly. Hence, this illustrates how students can design a system where the original physical measurement can be converted into an accurate and usable measurement through calculated conditioning techniques. The evaluation of the analysis provided by the students demonstrates the direct correlation between their student analysis of signal conditioning and the performance evaluation criteria established for CLO4. This occurrence demonstrates some level of competence by the students in their knowledge of the metrics associated with instrumentation. The low dispersion in the data set, ranging from 19.33 cm to 19.45 cm, demonstrates a high level of repeatability in the results. Therefore, students were able to provide evidence of both the precision and repeatability of the system through a quantitative measurement. The distinction made by the students between random variation and "systematic bias" has allowed for the categorization of the error types by the students, thereby fulfillling both the requirements for comprehensive data analysis and uncertainty analysis as outlined in the project requirements.

Additionally, students showed improvement on how to make an engineering decision based on the experimental result, instead of only interpreting raw data. Since the ultrasonic sensor produced a relative error of less than 3%, they concluded that the sensor is suitable for short-range distance measurement. This statement supports the final evaluation stage of CLO4, where students are expected to judge whether the performance of a system is acceptable for its intended application. By combining error analysis with practical testing, the students demonstrated their ability to evaluate the usefulness of an instrumentation system in a real-world situation.

3.4 Analysis on Students' Satisfaction on Problem Based Learning Method

A satisfaction survey was conducted among 45 participating students through Google form to evaluate the effectiveness of the Project-Based Learning (PBL) approach in the MECH 2241 course. The feedback was categorized into the achievement of Course Learning Outcomes (CLOs), technical skill integration, and general pedagogical satisfaction.

Category 1: Achievement of Course Learning Outcomes

The survey results show a high level of students' confidence which reflects the high achievement of course outcomes. For CLO1 (Explain basic principle of instrumentation, measurement and sensors technology) and CLO2 (Select suitable sensors and actuators for target applications), average of 92% of the respondents "Agreed" or "Strongly Agreed" that the project improved their competencies as shown in Figure 6. Figure 6 contains 4 questions which are

- This project improved my ability to explain the basic principles of instrumentation and sensor technology (CLO1)

- Through this project, I feel more confident in selecting suitable sensors and actuators for specific engineering applications (CLO2)
- I have a better understanding of how to apply signal conditioning (amplification, filtering) to digital measurement systems (CLO3)
- The use of Python, ARDUINO Serial Monitor, MATLAB Scope visualization helped me evaluate the performance and dynamic response of the instrumentation system (CLO4)

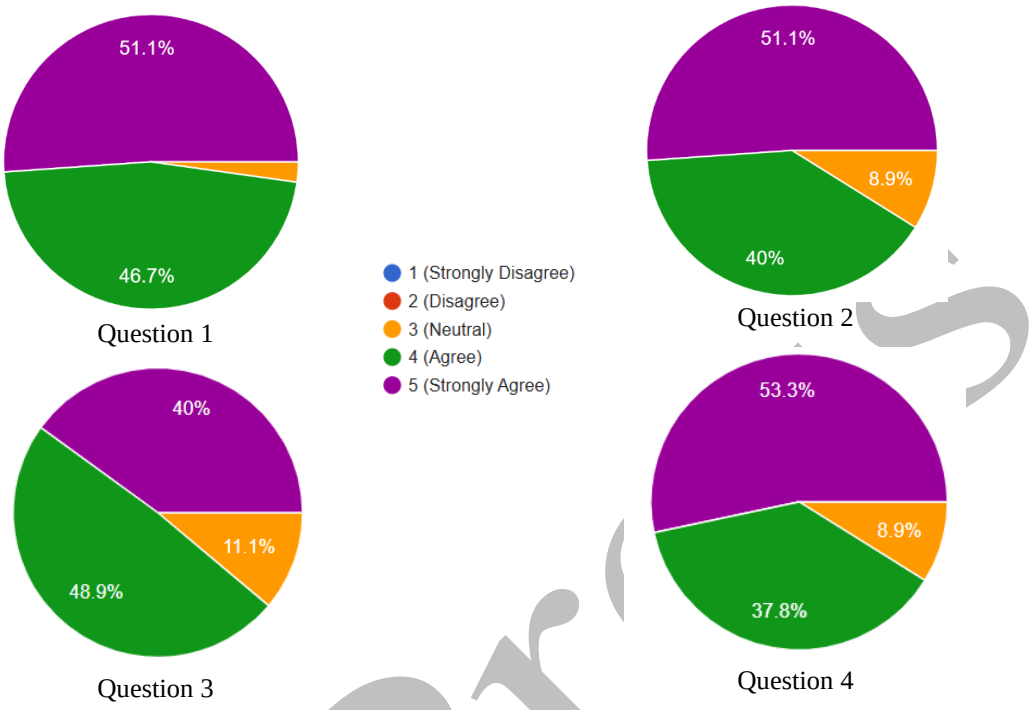


Figure 6. Students' satisfaction level for category 1

Interestingly, while CLO3 (Apply fundamental methods to design signal conditioning circuits for analog and digital target application) showed strong positive feedback, approximately 11.1% of students remained "Neutral". This suggests that the transition from hardware assembly to complex signal processing remains a challenging area for some students. However, CLO4 (Evaluate the performance of instrumentation system) received dominant support, with 91.1% of students feeling that the use of visualization tools like the Arduino Serial Monitor and MATLAB helped them effectively to evaluate the system's dynamic response. This suggests that the PBL framework successfully shifted student focus from passive observation to active performance analysis.

Category 2: Technical Skills and Tool Integration

This category aims to assess students on the ability to integrate various engineering tools to solve complex problems. The result is shown in Figure 7. The questions for this category are listed below.

- Integrating processing tools (e.g., Python, Simscape, or ESP32) with sensors significantly enhanced my understanding of Data Acquisition (DAQ) pipelines
- The use of dynamic, real-time data visualization (e.g., Live Plots, Scope blocks) was more effective for analyzing system behavior than reviewing static data tables.
- Investigating system anomalies helped me quantify the impact of environmental factors and measurement uncertainty.

The result shows that over 80% of students felt that the integration of Python, Arduino, and MATLAB was essential for the learning process. A critical finding in this category was that 93.3% of the students "Agreed" or "Strongly Agreed" that investigating system anomalies helped them quantify environmental factors and measurement uncertainty. This directly aligns with the students' technical report findings regarding the 2.75% systematic error in the ultrasonic sensor. By working with real measurement data, students were able to see that sensor readings are not always perfect or ideal. This helped them better understand measurement uncertainty, which is an important concept in instrumentation.

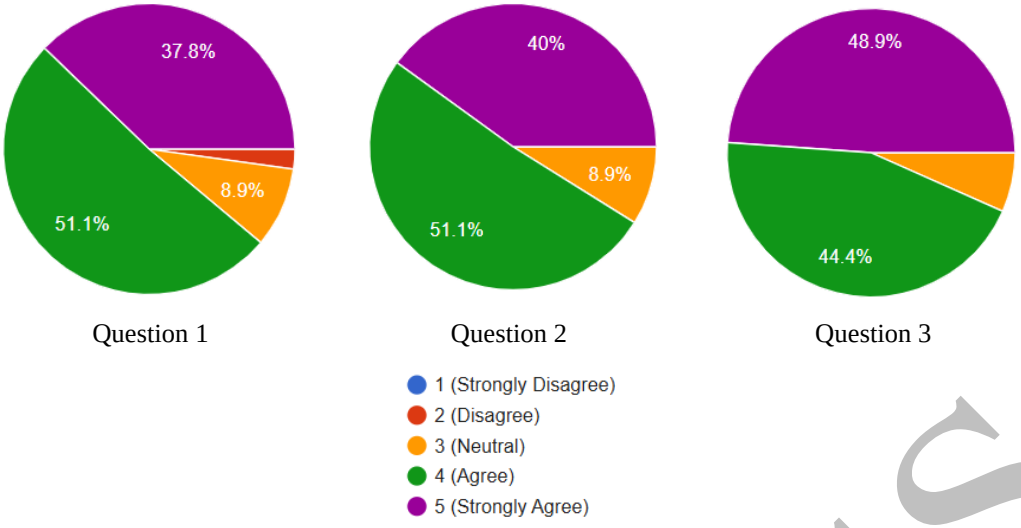


Figure 7. Students' satisfaction level for category 2

Category 3: General Satisfaction and Pedagogical Impact

The final category examined students' overall experience and how they perceived the value of the PBL approach. The questionnaire results are presented in Figure 8. This category included questions such as 1) This project-based learning approach increased my interest in the field of Instrumentation and Measurement, and 2) The hands-on nature of the project helped connect theoretical measurement concepts with practical engineering applications. The results show that 91% of the students felt that the hands-on project helped them connect theoretical concepts with practical engineering applications. In addition, the project also increased students' interest in Instrumentation and Measurement, with 60% of them strongly agreeing with this statement. The students' written comments also showed that they wanted more hands-on experiments and industrial examples in the learning process. One student stated, "Through this instrumentation and measurement, I know how things work out and how its implementation in real application". Overall, these findings suggest that the PBL approach not only helped students achieve the technical learning outcomes but also made the learning process more engaging and meaningful by linking academic theory with real engineering practice.

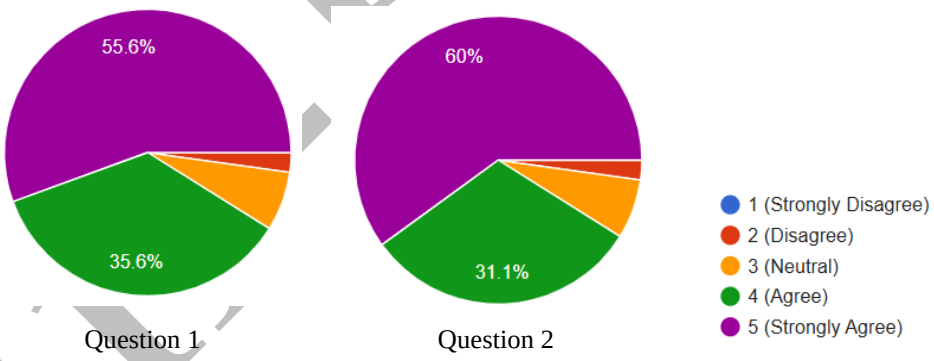


Figure 8. Students' satisfaction level for category 3

The results from the questionnaire on the students' perception of Problem-Based Learning (PBL) provide positive feedback. However, there are some limitations of this project including

- The survey used to measure students' perception was self-reported by students regarding their perceived learning and satisfaction levels with their PBL experiences and did not provide direct evidence of students achieving any competencies.
- The results were generated based on data from only one course cohort. Therefore, they will be considered a case study and should not be generalized across all instrumentation/measuring courses.
- Research in the future should include; pre and post tests, CLO assessment via rubric-based practices, and/or comparisons to traditional lecture-based methods in answering the learning question.

4. Conclusions

The successful integration of PBL as an instructional model to learn about instrumentation and measurement is evident in this project. The students used automation to create an automated braking system for reversing cars. This approach allowed students to move from the theoretical aspects of engineering to more complex problem-solving related to engineering. The technical results showed that the students successfully designed a high-performance system with an

accuracy of 97.25%. In addition, this high level of accuracy indicates that the students achieved the performance evaluation (CLO4) and signal conditioning (CLO3) components of the course.

The qualitative analysis of student satisfaction demonstrates that experiential learning has an extensive influence on student learning experiences in addition to the technical prototype. Students were able to investigate anomalies in the system while being able to quantify uncertainty in measurements, which resulted in the transition from potential hardware issues to critical learning milestones. Thus, there is a high degree of agreement, over 90% among students that the project has fulfilled its objectives to help students connect the theory and practice of engineering, demonstrating the important role of PBL in engineering curricula. This approach meets the Malaysian Qualifications Framework (MQF) Level 6 qualification requirements, in addition to meeting the global demand for graduates who are "workplace ready."

To further improve the learning experience and increase the technical complexity of MECH 2241, the course will require students to use multiple sensors for example infrared, LiDAR, and ultrasonic transducers to overcome data redundancy in "Complex Engineering Problems" (PO2). The technical complexity will also be increased by moving from simple threshold-based "On-Off" control systems to use of advanced control algorithms such as PID control to provide smoother deceleration and meet the objectives of higher-level mechatronics programs. In addition, IoT integration using the ESP32's Wi-Fi capability will allow for remote data logging and cloud-based performance measurement, aligning with "Industry 4.0" standards for industrial instrumentation. Finally, a longitudinal study comparing multiple student cohorts will be undertaken to determine the correlation between participant engagement with Project-Based Learning (PBL) and the longer-term retention of instrumentation concepts against traditional lecture-style assessments, thereby continuing to advance the use of evidence-based engineering education.

Acknowledgements
The authors gratefully acknowledge the Department of Mechanical Engineering, Kulliyyah of Engineering, International Islamic University Malaysia (IIUM), for providing the classroom facilities and supporting the discussions, experimental activities, and project-based learning implementation conducted as part of the MECH 2241 Instrumentation and Measurement course.

Funding
This study was not supported by any grants from funding bodies in the public, private, or not-for-profit sectors.

Declaration of Conflict of Interests
The authors declare no conflicts of interest.

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Ahmad H. Ahmad Hilmy: Data curation; Formal analysis; Visualisation.
Muhammad A. P. Awang Abdul Hisham: Methodology; Resources; Investigation.
Muhammad A. A. Mohd Rozailil: Validation; Investigation.
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Generative Artificial Intelligence Disclosure
Generative artificial intelligence (GenAI) tools were used solely for language refinement, including improving grammar, sentence structure, readability, and clarity during the preparation of this manuscript. All research, educational, experimental, data-collection processes and data analysis reported in this study were carried out by the authors, instructors, and participating students. The authors reviewed and verified the final manuscript and take full responsibility for its content.

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