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RESEARCH ARTICLE

Bridging theory and practice in motion detection: A reflective evaluation of PIR sensing systems by engineering students

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Abstract – This paper presents the experience of students' understanding in subject Instrumentation and Measurements. The approach of the study is to explore the real devices which is Passive Infrared or Pyroelectric Infrared to measure motion, by conducting a set of steps. Students need to do the calibration, design a system to capture motions and develop a real time monitoring using Graphical User Interface based on Python programming. This concept is different from the traditional method, which students just sit in the class and listen to the lecture. Through the experiment, the student team characterized the system's dynamic response and quantified random errors within a controlled environment. The result shows 93.72% of reliability and measured False Positive Rate of 153.09 triggers per hour. This finding leads to the students' satisfaction which are 80% in understanding the Data Acquisition pipeline, 80% in understanding the effectiveness of real-time visualization and 70% in understanding the analysis of uncertainty and false trigger. This project provides evidence on the effectiveness in Instrumentation and Measurement education by implementing problem-based learning which can improve the students' understanding in the foundational sensor physics in the modern IoT landscape.

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1. Introduction

Instrumentation and Measurement (I&M) is one of the important subjects that is critical for modern engineering expertise. This is because I&M provides the foundation for commerce and the innovation of improved instrumentation products [1]. Industry 4.0 forces practitioners to not only possess theoretical measurement concepts but also understand the daily operation of measurement equipment and how instruments are integrated into complex industrial processes [1, 2]. However, practice in I&M teaching and learning often suffers from an unreasonable setting of content and backward teaching modes, where laboratories play only a preliminary role in auxiliary theory teaching [3]. Unfortunately, this will often lead to an unsatisfactory outcome where the students, after completing their studies, will be unable to design or construct basic instrumentation systems [4]. The motivation for this article is to bridge the gap between theory and practice by shifting the educational focus from "what to learn" to "how to learn" [5]. While theoretical knowledge is important, the skill level in I&M expected by industries can only be gained through practical activities [2, 6]. To increase student motivation, the teaching delivery should be designed close to everyday life. This is because when humans learn by doing, using the body's sensory and motoric system, the impact of understanding the knowledge will be faster compared to only listening to a fact [5]. This paper presents an assessment of a student experiment on Pyroelectric Infrared sensors, also known as Passive Infrared sensors (PIRs). The educational concept employed here is Project-Based Learning (PBL), where a physical problem is presented to the student instead of only a theoretical explanation. Such an approach ensures that the student learns actively by studying the Generalized Measurement System and differentiating between the three stages of the system, which are sensing, conditioning, and displaying. Project-Based Learning is a holistic learning approach aimed at engaging learners in the exploration of specific issues [2, 7, 8]. On the other hand, conventional teaching approaches, where learners are first introduced to theories, Project-Based Learning involves starting with a problem that requires learners to investigate the issue to gain knowledge [9]. Thus, Project-Based Learning fosters active learning, thereby resulting in greater retention and the creation of success skills such as critical thinking and self-management [9]. Through a macro-instrumentation approach known as "system view", learners shift from studying the components of an issue to understanding the subsystem and system as a whole [10, 4].

In the Department of Mechanical and Aerospace Engineering, International Islamic University Malaysia, PBL is executed in the subject called MECH 2241, which is referred to as Instrumentation and Measurements. The list of projects to be performed by students is distributed in Week Seven before the mid-semester break to enable group formation. Some of the topics given to students include thermal mass systems, weight measuring, and vibration sensing. As can be seen, other topics included in the list are related to different measurements such as temperature and force. However, in this

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study, the topic of interest will be motion and vibration measurement, which will be conducted by using a hardware design approach. With the choice of the PIR sensor design project, the authors moved from theoretical foundations to "Hardware-in-the-Loop", which was required in the curriculum. In particular, the case of PIR sensing represents an example of all processes of a generalized measuring system, demonstrating how the fundamental stages from primary sensing to data presentation are effectively realized in a student-led engineering environment. In today's era, motion sensors play an important role in the development of automation systems, surveillance, and energy-saving measures, where they find their application in the form of automatic lighting systems and intruder alarm devices [11, 12]. Pyroelectric Infrared Sensors, also commonly known as Passive infrared or PIR sensors, find wide application in these areas owing to their low-cost factor, energy efficiency, and reliability for detecting human movement based on the change in infrared radiation emitted by the humans [13, 14]. Nevertheless, considering the field of instrumentation and measurement, a sensor is more than just a simple switch. It is a transducer that must be characterized through its static and dynamic transfer characteristics.

Even though PIR sensors are common components in automation systems for novice-level projects, there is still a substantial lack in the application of these devices in educational activities within the Instrumentation and Measurement discipline. Current approaches to incorporating such elements into classroom settings generally emphasize binary outputs for switching applications, providing minimal exposure to basic knowledge about measurement techniques, including system dynamics and signal processing [15, 16, 17]. Previous studies in engineering education commonly views the PIR sensor as a black-box component used in IoT systems, paying little attention to the characterization of static and dynamic behaviors [18]. This project addresses these gaps by moving from simple detection to the requirements that students must validate PIR technology through a detailed analysis of the "sensing-to-visualization" pipeline. This project addresses these gaps by applying the core competencies of the MECH 2241 curriculum:

- Sensor Selection and Application: Validating the use of PIR technology for target motion sensing applications (LO2).
- Data Acquisition (DAQ) and Signal Processing: Utilizing an Arduino microcontroller to convert physical thermal variations into digital logic signals via UART communication.
- Performance Evaluation: Analyzing the reliability and timing characteristics of the instrumentation system to identify environmental errors and false triggering (LO4).
- Real-time Visualization: Developing a Python-based platform to bridge the gap between raw data and meaningful engineering insights.

Real-time data logging and visualization will be combined into a complete "*sensing to visualization*" process. The proposed method provides a systematic investigation of the Generalized Measurement System, allowing engineers to go beyond sensing and systematically analyze the instrumentation system. The current paper is a study in practice of engineering education. In particular, the authors assess the role of the hardware-oriented project in transitioning from the physics of sensors to the implementation of a Generalized Measurement System. Although PIR sensors play a crucial role in control systems design [19, 20], this intervention concentrates on the Instrumentation Stage: signal conditioning, dynamic response modelling, and uncertainty assessment that constitute the essential "front-end" prerequisites for any stable control loop.

2. Materials and Methods

In this study, the Generalized Measurement System is adopted to map the physical infrared radiation to a digital data display. The methodology is divided into 4 parts which are the hardware selection, the development of a generalized measurements system, the design of control logic, data logging and calibration.

2.1. Hardware Component Specifications

To achieve Learning Outcome 2 (LO2), Select suitable sensors and actuators for target applications, the components selection is based on the technical compatibility and power requirements. Passive Infrared (PIR) sensor as shown in Figure 1 is used in this study. The complete setup is shown in Figure 2.

i. Transducers

HC-SR501 PIR sensor. This sensor has High sensitivity to 7–14 wavelength.

ii. Microcontroller

Arduino UNO, providing a 10-bit ADC capability and 9600 baud rates for serial transmission.

iii. Actuator

A Light-Emitting Diode (LED) with a 220 current-limiting resistor to indicate system status.

2.2. The Generalized Measurement System

The system architecture is divided into three stages according to the course curriculum:

i. Primary Sensing Stage

The HC-SR501 PIR sensor, illustrated in Figure 1, serves as the input transducer. It uses a pyroelectric component that detects any infrared heat changes due to human presence.

ii. Signal Conditioning and Variable Conversion Stage

The circuit has a BISS0001 IC chip. This stage executes crucial signal conditioning operations such as amplification and bandpass filtering in order to convert an analog signal to a digital logic signal (0V or 5V).

iii. Data Presentation and Transmission Stage

Arduino UNO (ATmega328P) microcontroller handles the logic signal. Using the UART serial protocol, the data is sent to a personal computer (PC) for displaying the measurement result.

Figure 1. PIR Sensor Module

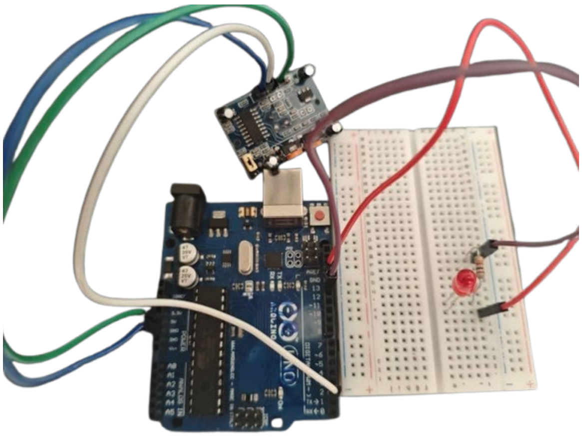

Figure 2. Experimental Setup

Figure 3 shows the internal block diagram of the BISS0001. The IC adopts a dual-stage operational amplifier configuration. The first stage is a high-gain amplifier, which is used to amplify the weak pyroelectric signal. The second stage is a band-pass filter, which is normally set at 0.3Hz-7Hz. The implementation of this band-pass filter is to remove any DC offsets due to temperature changes in the environment and any high-frequency noise.

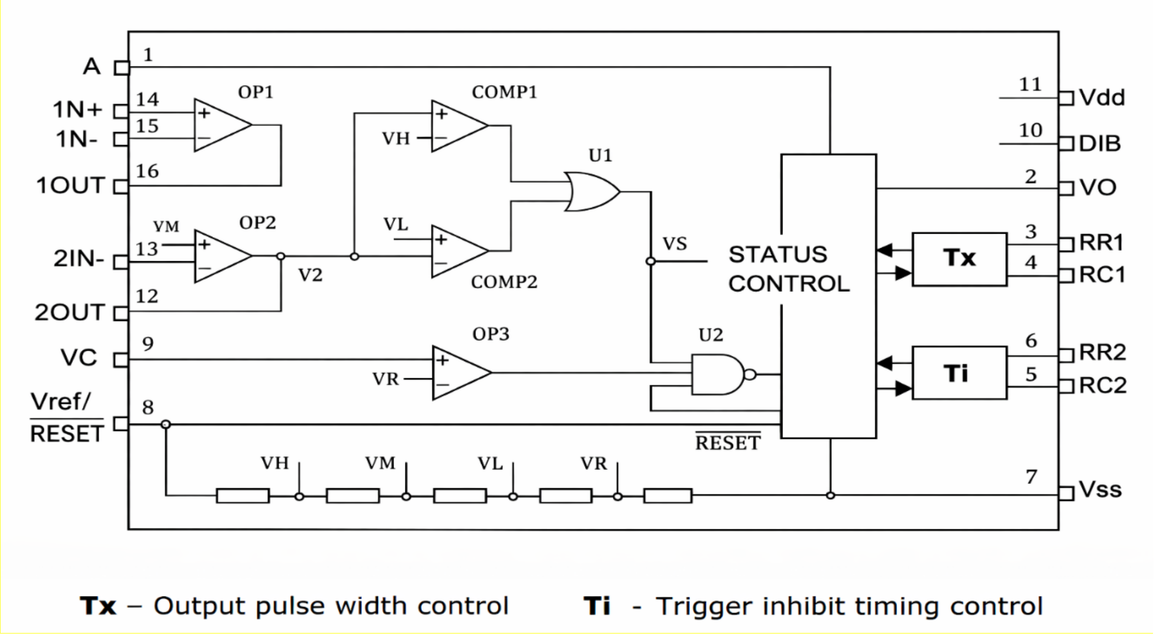

Figure 3. Internal Block Diagram of BISS0001

2.3. Control Logic and Sampling Strategy

The system operation follows an event-driven control logic. The process is performed by using Arduino UNO. The objective is to provide a systematic approach for the motion data collection. Figure 4 shows the 2 phases process performed in this study. The first phase involves a compulsory calibration duration of 2000 milliseconds for the PIR sensor to establish a stable IR background against the thermal interference. When the system becomes stabilized, it moves to the next phase which is a continuous polling process. In this phase, it measures the digital output of the HC-SR501 detector. The control algorithm is then split into two different states:

i. **Active State (Logic HIGH)**

When there is an event where a temperature difference surpasses the defined threshold level, the system initiates an "OPEN" state. During this mode, the microcontroller turns on the LED actuator and sends a Logic 1 through the UART. To measure the system behavior, a delay period is set up to last 10 seconds. This is defined as the holding time, which will prevent any signal from oscillating and guarantee a steady observation of the event within the Python visualization module.

ii. **Idle State (Logic LOW)**

When there is no motion detected, the system assumes a "CLOSE" condition (Logic 0). In this period, the sampling technique will be based on maximum stability with a 1-second sampling rate. Dual-rate sampling makes sure that the system can detect high-frequency activity and yet remain low on data redundancy during idle times.

By following the systematic flowchart in Figure 4, the project is expected to effectively prove that a stimulus is converted into digital form. The objectives for Signal Conditioning and Performance Evaluation (LO3 & LO4) can be achieved.

2.4. Data Logging and Calibration

In case of Learning Outcomes 3 (LO3), Apply fundamental methods to design Signal Conditioning circuits for target application (analog and digital), the Arduino communicates data in a well-defined format that is compatible with CSV: Time (ms), Status, Voltage (V). A calibration cycle of 2000 ms is incorporated on startup to give time to the PIR sensor to stabilize against the background IR noise.

The data presentation phase of the instrumentation system involves a script written in Python with the aid of Matplotlib and PySerial modules. The approach adopted is logical and sequential in nature to analyze the sensor's performance.

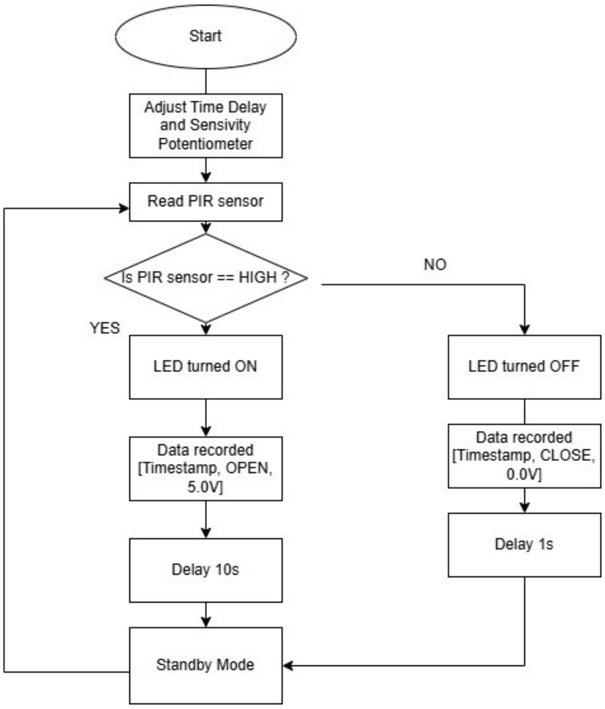

Figure 4. Flowchart of PIR Sensor Module Operation

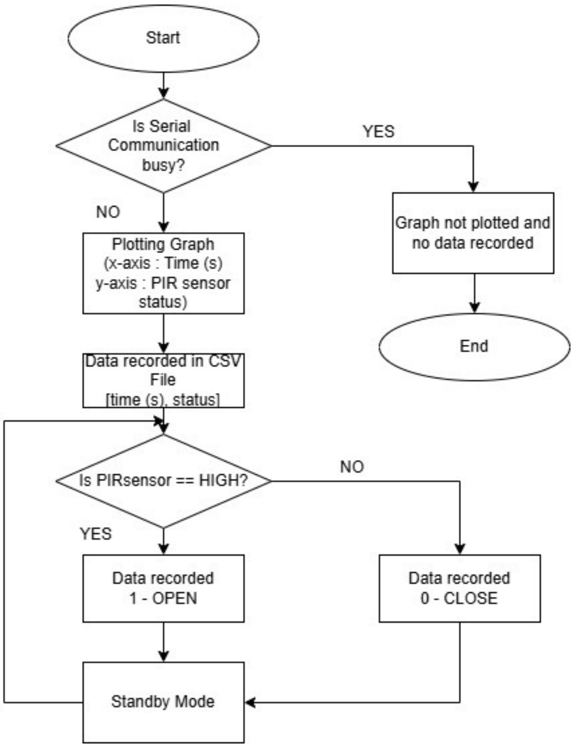

Figure 5. Flowchart of User Interface

Figure 5 shows the software flowchart. First, the code will set up the UART serial link with a baud rate of 115200. When the communication link is working properly, the program enters an endless loop of operations containing the following four blocks:

i. **Data Acquisition and Parsing**

The script checks for any strings in the serial buffer sent by the Arduino board. It then changes the string text ("OPEN" or "CLOSE") into integers (1 or 0) required for plotting on a graph.

ii. **Temporal Tracking**

To measure the dynamic behavior of the PIR sensor, the script determines the amount of time (t) elapsed since the beginning of the experiment for every data point. This allows for the precise measurement of the sensor's holding time.

iii. **Real-Time Visualization**

The *FuncAnimation* module allows the code to update the live graph dynamically. The graph setup includes the "sliding window" feature (auto-scrolling x-axis), enabling the observer to track the instant logic state changes while keeping an eye on the past trends.

iv. **Persistent Data Logging**

In addition to process 3 (Real-time visualization), each time-stamped data value is added to a CSV file, securing the experimental data for future calculations, such as determining the average active period or assessing how often the false trigger occurs in the environment.

A 2000 ms calibration process is included in the program initialization stage to allow the PIR sensor warm up and become stable to external infrared disturbances prior to measurement. To determine the influence of the calibration procedure on measurement precision, both calibrated and non-calibrated start-ups were compared. During uncalibrated operations, the sensor detected a "false high" signal (5.0V) during the first 500ms after powering on due to the sensor's pyroelectric crystal becoming thermally balanced with the surrounding space. The temporary noise produced has an uncertainty of about 40% in measurement within the first two seconds of operation. On the other hand, with the 2000ms delay, the sensor was able to start up in a "CLOSE" condition, where the voltage is zero, thus reducing the false trigger probability to 0%. From this step, students can see the importance of giving time for stabilization within dynamic measurement systems as stated under Learning Outcome 3 (LO3). The integration of Python-based Data Acquisition (DAQ) pipeline is expected to fulfil the Course Learning Outcome 4 (LO4), transforming from a simple hardware indicator to a real comprehensive system capable for advance performance evaluation.

3. Results and Discussion

In this section, the findings related to the actual implementation of the PIR sensor are outlined, thus transcending the limitations of the common “black-box” method used in the early stage of automation courses. In contrast to the usual education practices that pay much attention to activating the binary outputs, here the dynamic characteristics of the system’s transfer function are described via precise signal measurement. Using the real-time data visualization feature of the program written in Python, the project achieves a successful transition from IoT connectivity to the fundamentals of Instrumentation and Measurement. In the following analysis, various physical situations are considered, namely, Box Open/Closed scenarios.

3.1. Graphical User Interface

The design and implementation of the Real-Time Graphical User Interface (GUI) is a crucial stage of this project. The aim is to translate digital information into an output that is user-friendly. As shown in Figure 6, the purpose of the GUI is to establish a connection between the hardware ESP32 and the graphic representation of its thermal state. The GUI serves several vital functions that enhance the operational efficiency of the PIR sensing system:

- **Real-Time Status Visualization:** The operator can instantly distinguish between “Box Open” and “Box Closed” states through clear text indicators and color-coded background changes.
- **Persistent Historical Tracking:** Unlike standard serial monitors, the developed GUI maintains the entire history of detections on a moving x-axis. The analysis of the duration and frequency of motion events over time can be analyzed easily.
- **Cognitive Alerting:** The GUI is designed to give color-based warning alert. A “Flash Red” during a detection event will reduce the operator’s response time compared to reading raw numerical logs.

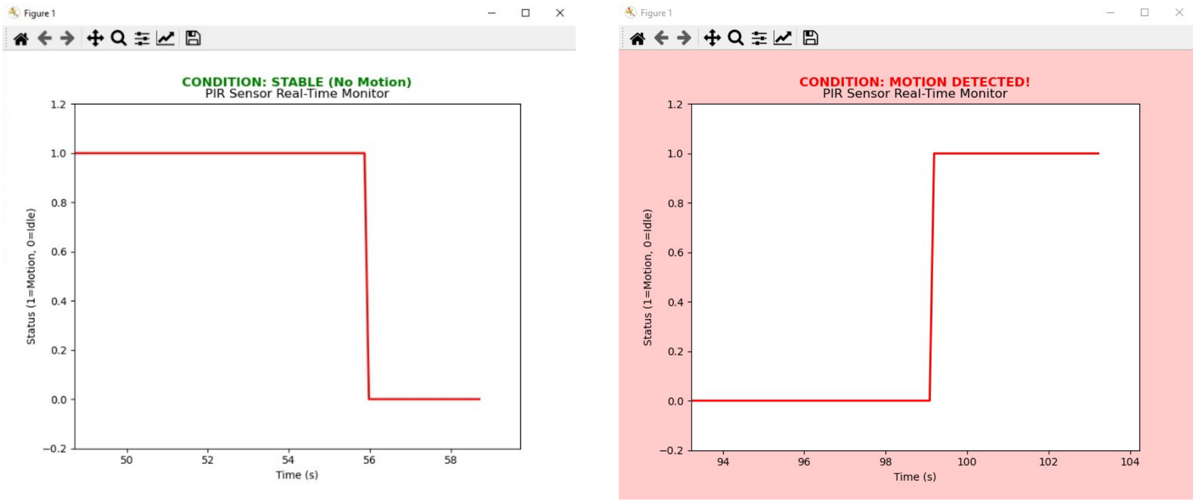

Figure 6. Graphical User Interface (GUI) to show the Status of the Sensor Reading

The GUI is developed using the Matplotlib module in Python programming language, and the asynchronous approach for data processing is used to keep the system highly responsive.

i. An asynchronous serial link with a baud rate equal to 115200 is implemented to avoid delays and to ensure that the depiction of the sensor's real-world condition is nearly real-time.
ii. The *FuncAnimation* module is used at the center of the GUI, which calls an update function periodically within 20–50 milliseconds. The rapid periodic polling helps the program to detect and show any sudden temperature spikes observed by the PIR sensor.

iii. *Blitting* is applied as a tool to address the latency issues associated with real-time plotting. The idea here is that only the trace of the graph and the status message are updated for each frame. This is significant in lowering the workload placed on the CPU.

iv. The x-axis represents a sliding window. With the passage of time, the axes will be refreshed such that the maximum value of the x-axis can be updated (e.g., $new_{xmin} = current_{maxTime} - 15$).

v. The GUI logic follows directly from the Differential Principle of operation of the PIR sensor. Whenever there is detected infrared flux such that ($Slot_A - Slot_B \neq 0$), then the system switches to "BOX OPEN" mode, while when the environment stabilizes with ($Slot_A - Slot_B = 0$), then the system returns to "STABLE" mode.

Experimental observations demonstrate that the PIR sensing system responded consistently to changes in infrared activity, satisfying the requirements for digital signal conditioning (LO3). The recorded measurements indicate transitions between stable, open, and partially open conditions during the experiment. Table 1 summarizes the sequence of recorded box conditions and important events obtained through the Arduino Serial Monitor during the data acquisition process.

Table 1. Data Logging Via Arduino Serial Monitor

Time (Seconds)	Box Condition	Notes
18	Open	Start baseline
22	Closed	Motion detection triggered
36	Open	Continued detection
54	Closed	Reset to stable
80	Open	Second detection
100	Closed	
120	Half-Open	Testing partial IR change
124	Closed	
140	Half-Open	
150	Fully Open	
160	Fully Closed	
176	Half-Open	
190	Closed	
200	Opened	
210	Half-Open	
220	Closed	
250	Half-Open	
260	Fully Open	
270	Closed	
280	Fully Open	
300	Half Open	
310	Fully Closed	
330	Open	End of logged data

3.2. Measured Data Analysis

To test the reliability of the HC-SR501 detector, its output signal was compared with experimental data obtained from manual recording of the status of boxes. Based on result shown in Figure 7, it can be observed that the sensor possesses high time accuracy in changing from the LOW to HIGH (1) state upon opening the box. High time resolution shown in Figure 8 allows for an effective separation of static state detection from motion recognition. Notably, during "Box Open" where the ground-truth value equals 1.0, the following phenomenon is observed. The enclosure is kept open during the entire process, allowing the operator's hand to be close to the PIR sensor. This scenario was chosen to ensure that the HC-SR501 follows the differential principle of changes in infrared radiation. It can be seen from the "Measured Status" column below that the sensor stays HIGH (1) as long as the hand is moving. This clearly demonstrates that the role of PIR sensors is not limited to being limit switches in the presence/absence state of the box, but that they are actual motion detectors. The result shows that the sensor is still activated despite the constant box geometry and complete openness of the box because the operator's hand creates a transient movement of heat energy on both pyroelectric sensors. The result is that there will be non-zero differential between both Slot A and Slot B ($Slot_A - Slot_B \neq 0$). This movement of heat energy is recognized as motion by the BISS0001 IC. This result is particularly relevant to the Instruction and Measurement course from a learning perspective.

3.3. Explanation of PIR Mechanism

The HC-SR501 detector utilizes a pyroelectric component divided into two separate areas, which are termed as slots or poles. Under the state "Box Closed," the inside of the box becomes thermally balanced, leading to the same thermal signatures on both slots. Because the internal electronics of the detector analyze the contrast between the two regions, a balanced temperature will create a zero differential ($Slot_A - Slot_B = 0$). Therefore, a LOW (0) output is generated. Hence, the detector is passive because it does not depend on the actual temperature but only on thermal contrasts.

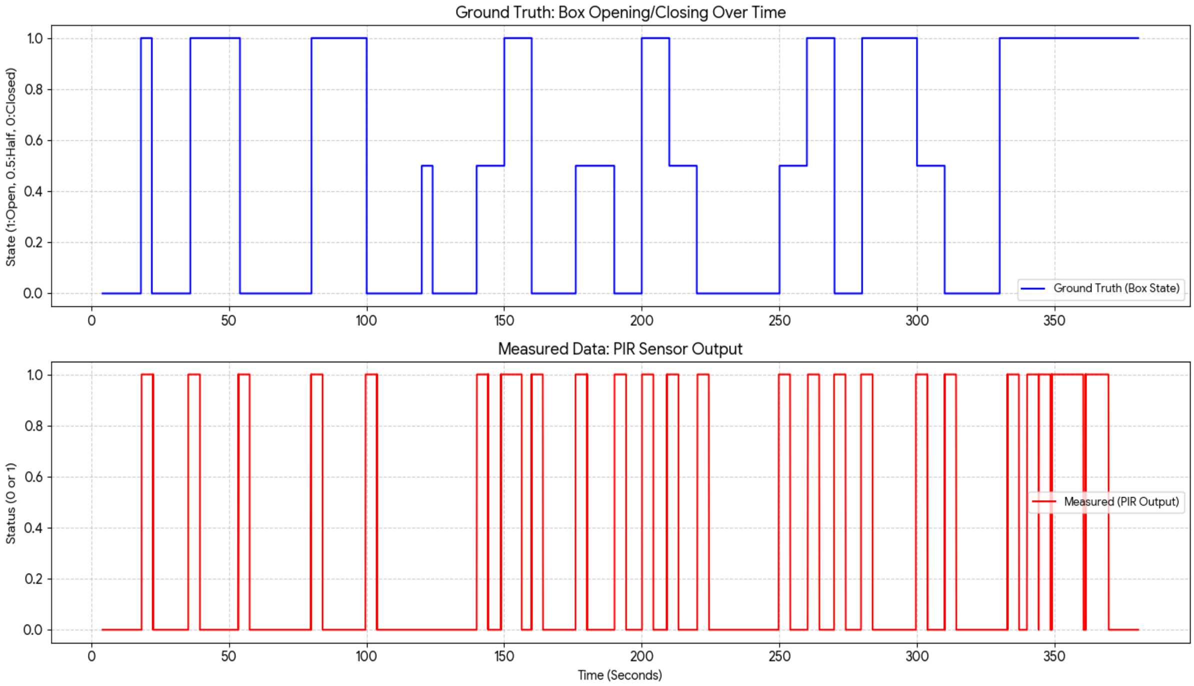

Figure 7. Sensor's Time Response Recorder by Python Based GUI

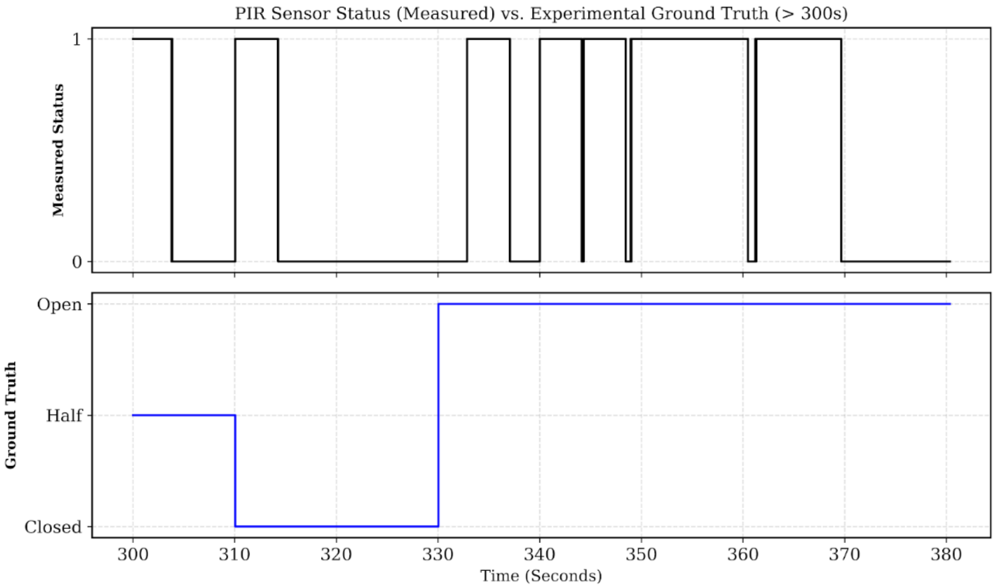

Figure 8. Comparative Analysis of PIR Sensor Performance vs. Ground Truth (t > 300s)

Once the cover is removed, there is an immediate change in the infrared flux since the infrared radiation from the environment and the operator's hand falls within the view of the sensor. As the infrared source moves past the sensor, there will be a gradual shift in position past the first pyroelectric slot and then to the second one, resulting in a sudden rise in temperature, creating a thermal peak or positive differential voltage. These changes are then analyzed by the comparator IC BISS0001 before sending the HIGH (1) signal seen in the Python graph.

The summary of the findings is provided in Table 2.

Table 2. Findings from the experiment

Experiment Phase	Observation	Scientific Conclusion
Box Closed	Status = 0	Thermal equilibrium: no IR differential detected.
Box Opened	Status = 1	Rapid IR flux detected across pyroelectric slots.
Half-Open	Status = 1/0	Partial IR change; depends on the speed of movement.

3.4. Quantitative Performance and Error Analysis

To undertake an overall assessment of the effectiveness of the sensor, the quantitative error rate was estimated based on a comparison between the output generated by the sensor and the manual ground truth logging. The findings presented in Figure 7 are presented in Table 3. From Table 3, it is evident that the sensor shows significant reliability (93.72%) in retaining stability when there is an obstruction of the infrared flux. In particular, the error rate (153.09 triggers per hour) can be explained by the internal thermal noise and air convection in the enclosed enclosure. The low Open State Consistency (36.02%) is indicative of the operation of the Differential Principle, where the sensor switches back to its default state (“0”) when the infrared energy stops moving, where the operator withdraws their hands from the enclosure.

Table 3. Quantitative Performance and Error Rate Analysis

Metric	Measured Value	Scientific Interpretation
Total Observation Time	376.24 Seconds	Duration of the manual observation and digital log.
False Positive Count (FP)	16 Events	Total number of events with “Status 1” when the box was confirmed closed.
Calculated Error Rate	153.09 Triggers/Hour	Frequency of false detections in a static thermal environment.
Closed-State Reliability	93.72%	Percentage of time the sensor correctly maintained a “0” status when the box was closed.
Open-State Consistency	36.02%	Percentage of “Status 1” during the “Box Open” state.

3.5. Pedagogical Impact and Students’ Perception

One of the main objectives of this assignment is to confirm the effectiveness of the Project-Based Learning (PBL) technique in achieving the learning objectives of the MECH 2241 Instrumentation and Measurements course. At the conclusion of the assignment, the students evaluated themselves and conducted a peer survey to determine the value of the assignment. Evidence for effective learning was observed in the form of the ability of the student group to recognize and describe Random Errors in an actual instrumentation setting. Despite a poor theoretical grasp on uncertainties at the beginning of the experiment, the precise monitoring process revealed a False Positive Rate of 153.09 errors per hour. The practical observation of thermal noise, especially with the 93.72% accuracy obtained when the Box was closed, offered a tangible basis upon which the student group could employ error analysis and noise reduction techniques.

Table 4 shows the responses of the student participants who took part in the technical process. It becomes clear that there is a 100% positive attitude towards the operating principle of the PIR sensor and Python monitoring. Nonetheless, one should consider the fact that these numbers are derived from a case study conducted among only five students who were responsible for the research (n = 5). The information collected reflects student perceptions related to their experience gained through this process.

Table 4. Students' perception of technical skill acquisition (n = 5)

Learning Metric	Percentage of Satisfaction	Correlation to Course Outcome
Understanding of DAQ Pipelines	80	**LO1 & LO3**: Basic Principles & Signal Conditioning
Effectiveness of Real-Time Visualization	80	**LO4**: Performance Evaluation of Systems
Analysis of Uncertainty / False Triggers	70	**Week 2**: Analysis of Experimental Data

*Note: These metrics align with Course Rubrics for grading the project

In addition to measuring subjective satisfaction, the objective effectiveness of learning was gauged using grading criteria for the course. The student group exhibited knowledge of LO3 (Signal Conditioning) through proper recognition of the function of the BISS0001 chip as a band-pass filter and LO4 (Performance Evaluation) in terms of determining the temporal uncertainty in the system. The high mean value achieved in Real-Time Visualization (80%) proves that seeing the live waveform of the PIR sensor’s logic state was much more efficient in comprehending “holding time” than looking at the corresponding datasheet. In addition to that, the notion of “false triggers” helped put the concept of Measurement Uncertainty into practice, thus turning a purely theoretical notion into an engineering problem. Thus, the presented results prove that a project-oriented approach is extremely efficient for learning about modern instrumentation techniques.

In addition to these specific measures, the PBL strategy significantly boosted students’ interest in the discipline of Instrumentation and Measurements, as all participants reported an increase in their level of interest (100%). The most common recommendation for future development was that the project be started sooner in the semester.

The importance of this project from a student’s point of view was that it provided a key link between the theory learned in the MECH 2241 course and engineering problems that one can experience in practice. Though lectures in the classroom provide the mathematical background for understanding the measurement uncertainty and principles of sensor design, the practical realization of the PIR system demonstrated how things work. Use of Python-based visualization turned out to be quite revolutionary, moving the learning experience from “black box” perception, when the sensor simply turns on the LED, to a detailed understanding of the dynamics of the entire system. By analyzing the dynamics of parameters such as hold times and logic states, the group was able to gain a direct understanding of Course Learning Outcomes 3 and 4, namely, regarding digital signal processing and assessing the system performance. In essence, through the completion of this project, students gained a better understanding of how engineers think and learned about the importance of the visualization of data in modern measurement systems.

4. Conclusions

This project has effectively shifted from treating the PIR sensor as a black box automation component to an instrumental case study in Instrumentation and Measurement (I&M). By reconsidering the system not only as a black box automation system, but also it gives binary outputs when certain events occur, the students were able to determine the dynamic behavior of the PIR sensor by using the Python programming language in data acquisition. The team demonstrated the learning progress based on the ability to recognize and calculate Random Error rates. Even though the team did not fully grasp the concepts of uncertainty at first, the practical demonstration of a false positive rate of 153.09 events per hour, caused by thermal changes in the environment, gave us the context to implement the error classifications and reduction process. A Closed State Reliability of 93.72% provides proof of concept that the design of the experimental setup can stabilize the IR energy source to be measured.

To develop further on top of the instrumental framework developed from this experiment, the subsequent steps include improving both the accuracy and scalability of the measurement setup. One of the key aims is to implement better digital signal processing (DSP) algorithms, such as adding a low-pass filter using the Python GUI application to counteract thermal noise. Moreover, the project will look at the shift from motion detection in binary form to advanced recognition of human activities by using machine learning techniques that study the morphology and amplitude of the consistent infrared signal. Lastly is to achieve educational reach by incorporating the local data-logging system within an IoT cloud environment. This is to provide a comprehensive analysis on how network latency and jitter affect the accuracy of measurement in remote laboratory settings.

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Declaration of Competing Interest

The authors declare no conflict of interest.

CRediT Authorship Contribution Statement

M. Nazhif A. N. (Supervision; Resources; Validation)
M. Danish P. Z. (Project administration; Software; Writing - original draft)
M. Iman A. H. (Visualization; Conceptualisation; Writing - review & editing)
Z. Nazhan Z. (Investigation; Data curation; Writing - review & editing)
M. Naufal Mohtar (Software; Formal Analysis; Methodology)
Luhur Bayuaji (Conceptualisation; Methodology)
Hazlina Md. Yusof (Conceptualisation; Methodology)
Dwi Pebrianti (Conceptualisation; Methodology; Validation; Writing - review & editing; Supervision)

Availability of the Data and Materials

The data used to support the findings of this study are included within the article.

Ethical Declaration

This research did not involve any human participants, animals, or sensitive personal data. Therefore, ethical approval was not required. All data used in this study were obtained from publicly available sources and used in accordance with relevant guidelines and regulations.

Generative Artificial Intelligence Declarations

The authors used AI-based tools solely for language editing and grammar refinement. No content generation or data interpretation was performed by AI. All intellectual contributions are original and solely attributable to the authors.

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