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From Detection to Deception: Enhancing PIR Motion Sensors in Office Environments with MIRA

Keeping the lights on

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Abstract: Pyroelectric infrared (PIR) motion sensors are effective in reducing energy consumption but often fail to detect static occupancy, leading to user discomfort. This project explores the integration of robotic extensions in office environments with motion-activated lighting systems to address their inefficiencies in detecting static users. The project introduces MIRA (Motion InfraRed Activator), a robotic extension equipped with an infrared (IR) laser specifically developed to deceive PIR occupancy-based sensors upon detecting lighting changes. The research encompassed several phases, including interviews with clients to determine design requirements, testing of light sensors to establish the operational thresholds, and experimental setups to evaluate the effectiveness of the IR laser in triggering a PIR sensor. The findings revealed that MIRA could successfully deceive motion sensors within a limited range but faced challenges at extended distances. This project demonstrates the potential for robotic enhancements to improve the accuracy and user experience of PIR motion sensor-based lighting systems.

1 Introduction

Approximately one-fifth of the energy consumed in office environments can be attributed to lighting. Therefore, it is no surprise that in offices, this particular energy consumption plays an important role in environmental impact and energy costs (Dubois & Blomsterberg, 2011). Motion-activated lighting sensors have been widely accepted as efficient energy-saving systems. They are also known as occupancy-based lighting control systems, by automatically turning on lights when occupancy in their vicinity is detected. Systems of such similarity can result in significant energy savings in office environments (Jennings et al., 2013).

General motion sensors make use of pyroelectric infrared (PIR) motion sensing technology, which detects changes in emitted infrared radiation by objects within its field of view (Puspita Mouri et al., 2016). Two infrared (IR) sensitive sensors are present in a PIR sensor. All objects with a temperature higher than absolute zero emit infrared radiation, where a higher temperature will result in more emitted radiation. When a warm object passes the PIR sensor, the first internal IR-sensitive sensor sends a positive signal, while the second internal sensor sends a negative signal. For a visual representation of the inner workings of a PIR sensor, see Figure 1.1 (Cypress, 2021). The PIR sensor reacts to the difference between the two internal sensors. A signal is sent that motion has been detected only when there is a polarity difference between the two sensors. Then, once motion has been detected, the motion-activated system is triggered, turning on the lights or activating other connected systems.

A downside of these sensors is the lack of individual optimization (de Bakker et al., 2016), which can lead to undesirable user experiences. As an example, in office environments where desk presence remains undetected, motion-activated lighting can switch off while people are still working. False negatives occur when the PIR sensor fails to detect occupancy even when users are present, leading to the lights turning off. These false negatives related to undetected occupancy also lead to a decrease in the accuracy of the systems (Chu et al., 2021) and a de-

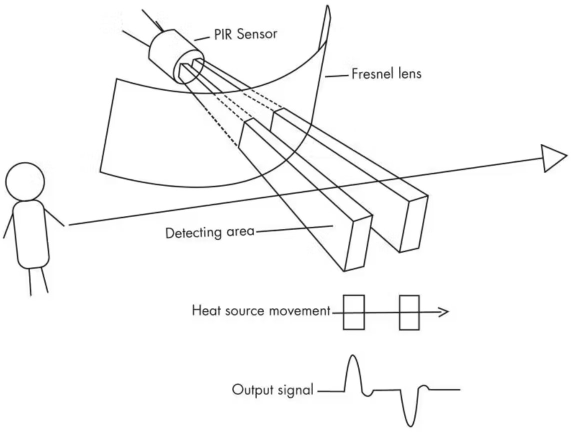

Figure 1.1: The working principle of a pyroelectric infrared (PIR) motion sensor. The sensor detects changes in infrared (IR) radiation within its field of view, using the two IR-sensitive sensors. A signal is sent that motion has been detected when there is a difference between these two signals. From Cypress (2021).

cline in user comfort. Considering these limitations, integrating robotic extensions can present a possible solution to these challenges. Whereas a light switch will undermine the idea behind occupancy-based lighting sensors (Haq et al., 2014), the incorporation of robotics allows for dynamic adjustments, without having to compromise on the user convenience or energy-saving benefits. It also allows for an increase in flexibility and individual adaptation in addition to the motion-activated lighting systems.

A possible solution was proposed by Andrews et al. (2020). Their approach included mounting the PIR sensor on a robotic platform. Through artificial movement of the platform, it enabled the PIR sensor to detect stationary human presence. This method allows the sensor to simulate the motion that is necessary for detection, thereby identifying static occupancy which still sensors miss. Another possible adaptation to a PIR sensor was developed by Wu et al. (2018). A module was developed that combines a mechanical shutter with the PIR sensor. The shutter alternately blocks and exposes the sensor to IR radiation emitted by human bodies, effectively causing the sensor to detect moving and stationary individuals. Both solutions increased the accuracy of the PIR sensor. However, since ceiling attachments are not feasible, the discovered solutions by Andrews et al. (2020) and Wu et al. (2018) cannot be utilized.

Instead, this project aims to develop an IR extension that can deceive the sensor by mimicking human presence. Rather than replacing, or adapting, the current occupancy-based sensor, this study looks into the low-cost, extended application of robotics in motion-activated lighting systems, increasing the accuracy of static user detection in offices. The design considerations and limitations of the extension should also be considered. By considering the diverse challenges, the following research question will be explored: What are the design considerations and what is the effectiveness when integrating a robotic extension to occupancy-based lighting control systems in office environments for enhanced user comfort?

To approach this study, the development of the device was divided into several distinct phases to ensure its functionality and effectiveness in real-world scenarios. Moreover, these phases were designed specifically for this project to address both technical considerations and user-related expectations systematically. The overall development can be separated into four different phases:

1. Determine Design Considerations: Conducting a structured interview with the clients to gather insights regarding their preferences and requirements. The physical design expectations and limitations of the device will be determined.

2. Light Sensor & Threshold Determination: Configuring and testing different light sensors to determine the most effective light sensor and the necessary corresponding threshold. This threshold is used to determine when the lights have turned off in the office, causing the final device to be activated. This phase includes setting up three different light sensors, determining experimental locations, collecting data over multiple sessions, and analyzing the data for stability, response time, and sensitivity.

3. PIR Sensor Deception: Using an IR laser to simulate human radiation, aiming to trigger a PIR sensor. An IR laser emits infrared radiation similar to that of a human body, which can trick the PIR sensor into detecting motion.

This phase tests the effectiveness of the laser regarding its activation of the motion sensor found in the office. It also involves discovering relationships and patterns between a PIR sensor and the IR laser diode. This phase includes setting up the laser and PIR sensor, combining them into a single setup, conducting experiments, and analyzing data from video footage.

4. Final Device: Integrating the components into a single device controlled by one central development board. The components are the selected light sensor with its determined threshold and the IR laser. This phase involves setting up the final device, testing it in the office, and analyzing its effectiveness in deceiving the PIR sensor and meeting the operational requirements.

The project is successful if the accuracy of the problematic occupancy-based lighting sensor has been significantly improved. Additionally, low-cost materials are of importance, to ensure that the money saved from the reduction in energy consumption by installing the motion-activated lighting systems, is not reinvested in these same lighting systems. Finally, client satisfaction will be an important factor in the success of this project, as this project would not have taken place without their input and requirements.

2 Methods

The development of the device is divided into four distinct phases to ensure its functionality and effectiveness in real-world scenarios.

2.1 Determine Design Considerations

A structured interview was conducted with the two clients to gather insights regarding their preferences and requirements for the robotic extension. The purpose of this interview was to understand specific expectations and constraints of the device. The contents of the interview that was made for this project covered topics related to placement, size, sound, mobility, user interaction, safety, maintenance, aesthetics and future scalability of the device which were to be taken into consideration.

2.2 Light Sensor & Threshold Determination

In this phase the configuration and testing of different light sensors takes place. This is done to find the most effective light sensor and establish the necessary corresponding threshold. The threshold will detect when office lights turn off, which will in turn trigger the final device.

2.2.1 Light Sensor Setup

Three different light sensors were used to measure the light intensity variations and determine when the lights turn off in the office. All sensors were chosen due to their small size, low cost, and availability. Additionally, the three sensors each portray different characteristics. Where the sensor module allows for relatively easy soldering attachments, the other two sensors are lower in cost and portray different resistance values in light and in darkness. The three sensors used are:

- Light-dependent resistor (LDR) GL5528; 10-20kΩ in light; 1MΩ in darkness;
- LDR GL5537; 20-30kΩ in light; 3MΩ in darkness;
- LDR Ambient light sensor module TEMT6000X01.

The sensors were attached to a breadboard that enables circuit connections and positioned adjacent to each other. The LDR sensors were installed at approximately the same height. Due to attachment limitations, the light sensor module is placed close to the surface of the breadboard. The three sensors were attached to an ESP32 development board, on which a simple sensor data retrieval code was programmed. A laptop was then connected to the ESP32 for logging the data retrieved from the sensors.

2.2.2 Experimental Locations

The extended device was designed for a specific office on the northwest side of the building. The experimental locations are all situated inside this office. A few possible placement locations were determined in collaboration with the clients; a closet on either side of the room. Both of these closets allow for placements close to the ceiling to avoid a hindering position of the device. A third location, a desk adjacent to the desks of the clients, was used to measure the impact of natural light alongside the artificial lighting in the office.

2.2.3 Data Collection

The data is collected over five different sessions. Measurements took place at different times of the day with varying types of weather. This was done to determine the effect of weather and daylight on ambient light levels. The setup was placed at the three experimental locations. Collection of the data occurred up to a few seconds after the lights in the room turned off, which would take approximately six minutes. For precise data collection, the program ran every one millisecond.

2.2.4 Data Analysis

The collected data was analysed, to compare the responsiveness to changes in light conditions of each sensor at different locations. Three metrics were used to assess each sensor's potential effectiveness:

- Stability: Consistency of the sensor output under various light conditions;
- Response time: The difference in time taken by the sensors to respond;
- Sensitivity: The degree of change in output relative to light variations.

The final assessment was aimed at identifying the most suitable sensor for accurately detecting when the lights have turned off. The threshold will be standardized across all experimental locations to ensure that movement of the device does not compromise its functionality.

2.3 PIR Sensor Deception

Here, an IR laser is used to simulate human IR radiation to see if it triggers a PIR sensor. The effectiveness of the laser in activating a PIR sensor will be determined, and the relationship between the PIR sensor and the IR laser diode will be explored.

2.3.1 Components

The following components were used in the PIR sensor deception phase:

- Breadboard: a construction base that allows for electrical circuit connections;
- ESP32 development board: serves as a central processing unit for controlling the other components;
- LDR: a light-dependent resistor that monitors light levels;
- Resistor: used to read the light levels from the LDR;
- PIR sensor: used to detect objects within its vicinity;
- Green LED: lights up when PIR sensor detection occurs;
- ADL-78051TL Infrared laser: used to trigger the PIR motion sensor;
- Transistor: acts as a switch for the laser;
- Voltage regulator: used to power the laser;
- Red LED: lights up when the laser is powered on;
- Camera: captures the experiment for subsequent analysis.

The components were primarily selected for their availability and because they were low-cost, which means that most of the components are interchangeable with similar elements. An exception is the ADL-78051TL laser, which is central in this experiment, as it is used to test its effectiveness in deceiving PIR sensors.

2.3.2 Laser Setup

To explore the feasibility of triggering a motion-activated system without human movement, an experiment was conducted using an ADL-78051TL infrared laser. This component was chosen for its ability to emit infrared light at a wavelength of 780 nm, which is what PIR sensors are able to detect.

The laser is attached to a breadboard using a transistor and a voltage regulator, as the regular pin output from the ESP32 is above the maximum allowed voltage of the laser. Through this setup, the laser could be controlled by one of the output pins passing to the transistor, ensuring that the voltage regulator will pass the right amount of voltage to the laser.

As the laser does not emit a visually detectable light, a red LED is attached to the breadboard parallel to the laser. This serves as a safety measure. In this way, visual feedback for when the laser was on could be provided, and accidental eye damage from the laser (Roithner Laser, 2021) could be prevented.

2.3.3 Sensor Setup

A PIR motion sensing detector module was used for the experiments, which is similar to the sensor present in the office. The obtained PIR sensor was connected to an ESP32 development board, logging the sensor's output when an object was detected. The PIR sensor was set to detect objects every two hundred milliseconds. A green LED was attached to the breadboard to serve as visual feedback from the PIR sensor. The green LED would light up when the PIR sensor detects an object.

2.3.4 Combined Setup

The laser setup and the PIR sensor setup were both connected to the ESP32 development board which would serve as a central processing unit that controls all components. The pseudo algorithm that is uploaded to the development board can be found in Pseudocode 2.1. This code was specifically written for this project.

The setup also involved the use of two measuring tapes. One measuring tape aligned with the laser setup, to measure the distance of movement. Another measuring tape was put between the laser and the PIR sensor, to measure the distance between the two setups.

Using this configuration, it can be determined whether the infrared laser component would successfully mimic human movement. Simultaneously, the setup was used to approximate how far and how fast the laser can move to be detectable by the sensor.

Algorithm 2.1 Arduino Interface Algorithm for PIR-Sensor-Based Object Detection and Laser Activation

```
Initialize Serial Communication at 9600 bps
Configure pin for PIR sensor as INPUT
Configure pin for light sensor as INPUT
Configure pin for green LED as OUTPUT
Configure pin for transistor as OUTPUT
repeat
  Read if object is detected by PIR sensor
  if object detected then
    Set transistor to LOW (turn off the laser and red LED)
    Set green LED to HIGH (turn on green LED)
  else
    Set transistor to HIGH (turn on the laser and red LED)
    Set green LED to LOW (turn off green LED)
  end if
  Delay 1000ms
until end of experiment or power down
```

2.3.5 Procedure

Experiments were conducted by manually varying the distance and the speed of the laser, and the distance between the laser and the PIR sensor. The laser diode was placed at a distance of ten centimetres from the PIR sensor and increased incrementally by one centimetre. Each distance consists of ten different trials. This process continued until a distance was reached where the sensor failed to detect the laser diode in most of the ten attempts, indicating a decline in detection accuracy. The response time of the PIR sensor was monitored and recorded.

The movement of the laser and its distance to the PIR sensor were gathered and measured using video recordings. This footage allows relatively accurate analysis by providing a reliable method to capture exact distances of laser movement, laser distance to the sensor, and time before PIR sensor detection.

2.3.6 Data Analysis

The video footage was analysed to extract precise data for the necessary variables that are to be retrieved:

- Distance to PIR sensor: The distance in cm between the laser diode and the sensor in which successful detection of the IR laser diode happens;
- Amount of movement: The necessary degree of movement of the laser in mm before sensor detection;
- Response time: The time in milliseconds until PIR detection;

During video footage analysis, the variables were put in a table and statistically analyzed to determine the operational thresholds of the laser diode in relation to the PIR sensor. The statistical analysis was performed by making use of the Python library `statsmodel` (Seabold & Perktold, 2010). Linear regression techniques were used to check if there were any significant linear relationships or patterns between the variables which could influence the setup and effectiveness of the deception.

Success would be measured by the laser's ability to trigger the obtained PIR sensor using the operational thresholds determined through statistical analysis. The PIR sensor would serve as a baseline, as it was assumed to be similar to the motion-activated sensor in the office.

2.4 Final device

The final phase is where all the previous components are integrated into a single device. The components include the selected light sensor with its corresponding determined threshold and the IR laser. For the final device, testing took place inside the office environment as this was its intended setting.

2.4.1 Device Components

The final device uses similar components as before. Only the PIR sensor was taken out of the setup.

- ESP32 development board: serves as a central processing unit for controlling the other components;
- LDR: a light-dependent resistor that monitors light levels;
- Resistor: used to read the light levels from the LDR;
- Infrared laser: used to trigger the PIR motion sensor;
- Servo motor: a motor that manipulates the position of the laser;
- Transistor: acts as a switch for the laser;
- Voltage regulator: used to power the laser;
- Red LED: lights up when the laser is powered on.

2.4.2 Device Setup

The ESP32 development board was used as a central processing unit. All other components were either connected or controlled from this board. The LDR is connected to the breadboard using the resistor, and connected to the development board using an input pin. The transistor and the servo are connected to an output pin. Besides that, the transistor is also connected to the voltage regulator, which in turn is connected to the laser and the red LED. Pseudocode 2.2 shows the representation of the algorithm that is uploaded to the ESP32. The threshold in pseudocode 2.2 is to be discovered in the light sensor threshold determination phase. The necessary movement value is to be determined in the PIR sensor deception phase.

2.4.3 Testing

The testing stage will take place inside the office, where it is to be determined if the final device is effectively deceiving the PIR sensor that is present. The focus is on verifying the device's functionality within its intended setting. This includes testing the device's ability to consistently activate the PIR sensor under various conditions, such as different times of day and varying levels of ambient lighting. The goal is to discover that the device can reliably operate without manual intervention, adhering to the requirements specified during the client interviews.

2.4.4 Data Analysis

The final phase of data analysis is necessary to determine that the assembled device meets the operational requirements. Its effectiveness will be determined by the following metrics:

Algorithm 2.2 Arduino Interface Algorithm for Light-Level-Based Laser Activation

```
Initialize Serial Communication at 9600 bps
Configure pin for light sensor as INPUT
Configure pin for transistor as OUTPUT
Initialize and configure servo
repeat
    Read light level from sensor
    if light level < threshold then
        Set transistor to HIGH (turn on the laser and LED)
        for position = 0 to necessary movement do
            Move servo to position
            Delay 15ms
        end for
    else
        Set transistor to LOW (turn off the laser and LED)
    end if
    Delay 1000ms
until end of experiment or power down
```

- Effectiveness of light sensor & threshold: One of the LDRs has been chosen, and the related light threshold has been determined. These two decisions are checked for inconsistencies.

- PIR sensor interaction: The device should be able to actively deceive the PIR sensor.

3 Results

3.1 Determine design considerations

An interview was performed with the two clients to determine the design considerations and limitations. The outcomes of the interview are summarized below.

- Placement: The clients specified that the device is not to be placed on walls or the ceiling, or areas where it might obstruct daily activities. Preferred placements included a closet on either side of the room.

- Size and sound: The device should be as compact as possible, minimizing its physical presence and noise output.

- Mobility: The device should exhibit minimal movement.

- User Interaction: Privacy concerns were highlighted, where specifically any recording features were not desirable. The device should not store or transmit sensitive data, particularly related to office presence.

- Maintenance: Minimal maintenance of the device is preferred, with the exception of battery changes. The clients also suggested the need that the device should be adaptable to changes without major redesigns.

- Aesthetics and Additional Features: By preference, the device should blend into the office environment.

- Future considerations: There is a possibility of an additional person in the office which should be taken into consideration.

Ultimately, the preferred placements were a closet on either side of the room. The device should be compact and exhibit minimal sound, and movement. Lastly, the device should also account for privacy concerns and future scalability.

3.2 Light Sensors Threshold Determination

The results of the light sensors threshold determination phase portray the differences in sensor performance, particularly in terms of stability, response time, and sensitivity. The data was recorded every millisecond to capture the precise moment the lights were turned off in the office. The three sensors were compared across the three different metrics.

3.2.1 Stability

The LDR Ambient light sensor module TEMT6000X01 showed inconsistent measurements across all assessment metrics. These inconsistencies were due to attachment difficulty. The sensor was loosely attached to the breadboard, causing the sensor to be unreliably connected. Therefore, the sensor failed to produce reliable data that could be used in determining the light threshold. As such, the sensor module accurately detected changes in light intensity twice out of all five measurements. Due to these inconsistencies, the TEMT6000X01 sensor was taken out of further consideration.

In contrast to the TEMT6000X01 sensor, both the LDR GL5528 and LDR GL5537 exhibited consistent and stable results across all assessment metrics. Results are summarized in Appendix A, Table A.1, which illustrates the consistency and reliability of the LDR GL5528 and LDR GL5537 sensors in detecting changes in lighting conditions. An example of the measured light intensity of the two sensors ten seconds before and five seconds after the lights turned off in the office can be seen in Figure 3.4. The Figure shows the fifth measurement from the desk location during cloudy weather, as well as an indication of when the lights in the office turned off. These sensors, LDR GL5528 and LDR GL5537, maintained uniform sensitivity and accuracy in response times across all measurements at the different locations, during varying times of the day, and with varying types of weather.

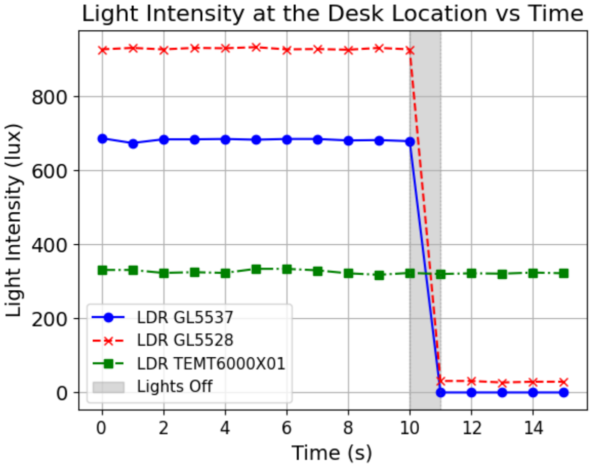

Figure 3.1: The light intensity values measured by LDR GL5528 and LDR GL5537. Ten seconds before and five seconds after the lights turned off in the office can be seen in the graph. The measurement took place on a desk in the office during cloudy weather.

3.2.2 Response Time

The response time of both the GL5528 and GL5537 sensors was found to be virtually identical, with no observable difference exceeding 1 millisecond. This similarity in response time indicates that these sensors are capable of detecting changes in light with no considerable difference.

3.2.3 Sensitivity

The sensitivity of the GL5528 and GL5537 light sensors was assessed by comparing the mean, standard deviation, maximum, minimum, and percentage change in light intensity values from when the lights were on to when they were off. These measurements were taken across three different locations: the left shelf, desk, and right shelf in the office, providing an understanding of each sensor's performance in the varying environments.

For the GL5528 sensor, the mean light intensity value when the lights were on ranged from 512.90 to 949.35 lux across the locations, dropping to near zero when the lights were off, with the percentage change exceeding 92% in all cases. At the desk location, the mean value decreased by approximately 92.80%. Similarly, the standard deviation and maximum values demonstrated substantial decreases, indicating the sensor's high sensitivity to changes in light conditions.

The GL5537 sensor exhibited similar trends, with mean values decreasing to zero or near zero when the lights were turned off, reflecting a 100% change at both the left shelf and right shelf locations. At the desk, the mean value decreased by 97.02%, showcasing a slightly higher sensitivity compared to the GL5528. Therefore, the GL5537 shows a slightly higher sensitivity overall which is based on the average percentage changes recorded.

3.3 PIR Sensor Deception

The main objective of using the laser diode was to assess its capability of successfully triggering a PIR sensor. To determine whether there is a significant relationship or pattern which can influence the setup and effectiveness of the deception using the laser diode, a simple linear regression between the independent and the dependent variables was performed in Python with the `statsmodel` (Seabold & Perktold, 2010) package. The independent variable was the distance of the laser to the PIR sensor. The dependent variables are the amount of change of the laser and the corresponding time of change.

3.3.1 Distance to PIR Sensor

The effectiveness of the laser diode was evaluated based on its ability to trigger the PIR sensor consistently across the range of distances. The experimental setup included gradually increasing the distance from the PIR sensor to the laser, starting from ten centimetres, and incrementing with one centimetre at each measurement. The measurements were conducted up to the point where the sensor's accuracy began to decrease. The predefined accuracy threshold was set to detect the laser in at least the majority of the ten attempts.

The detection accuracy for every distance with ten trials per measurement can be seen in Figure 3.2. A total of 295 data points were collected. At a distance of 40 centimetres, the motion-activated sensor successfully detected the laser in three out of ten trials. This decline in detection accuracy can also be seen in Figure 3.2. Since the performance at 40 centimetres was below the set accuracy threshold, no further measurements were conducted beyond this distance.

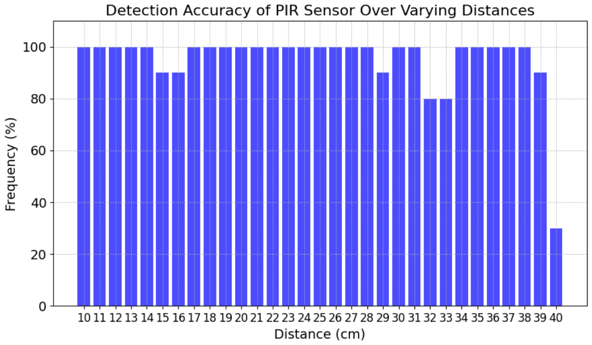

Figure 3.2: The detection accuracy percentage of the PIR sensor for an IR laser diode, measured over increasing distances starting from ten centimetres and incrementing by one centimetre per measurement. At each distance, ten trials are conducted until the sensor fails to detect the target for a majority of the trials. In total, 295 data points are presented.

3.3.2 Amount of Movement

The regression analysis revealed a statistically significant, but weak linear relationship between the distance from the laser to the PIR sensor and the amount of movement performed by the laser before the laser was detected by the sensor. The model's R-squared value was 0.03, indicating that approximately 3.6% of the variability in the amount of movement necessary for the laser to be detected by the sensor can be explained by the distance of the laser to the sensor.

The regression coefficient for the distance to the sensor was positive ($\beta = 0.0565$), suggesting that for every added centimetre to the distance between the laser and the PIR sensor, the amount of movement necessary for the laser to be detected increases by approximately 0.57 millimetres [F(293) = 10.98, p = .001]. The relationship between the laser's average amount of movement and the distance of the laser to the sensor can be seen in Figure 3.3. In this graph, it can also be seen that when the distance increases, more movement is needed to deceive the PIR sensor.

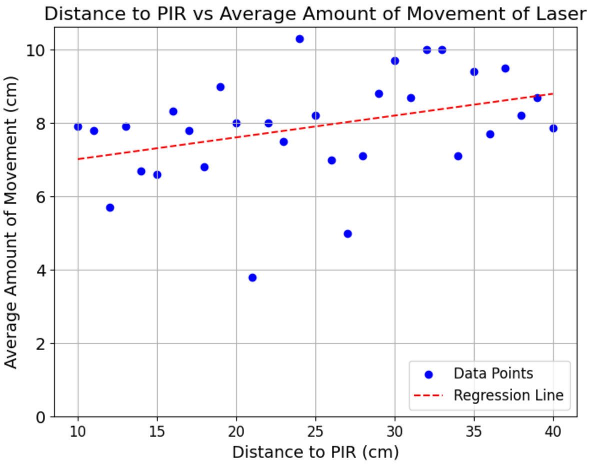

Figure 3.3: The average amount of movement necessary for the IR laser to be detected by the PIR sensor at varying distances incremented by 1 centimetre, beginning from 10 centimetres. Every interval consisted of ten trials. The regression line shows the relationship between the distance of the laser diode to the PIR sensor and the necessary amount of movement for the laser to be detected by the sensor.

3.3.3 Response Time

The regression model's R-squared value for the relationship between the distance of the laser diode to the PIR sensor and the time it took for the PIR sensor to respond was 0.011. This means that only 1.1% of the variability in the change in time of detection can be accounted for by changes in the distance from the laser diode to the sensor.

The coefficient for the distance of the laser to the PIR sensor was also positive ($\beta = 0.0101$), indicating that for each added centimetre to the distance between the laser and the PIR sensor, there occurs a minor increase in detection time. However, this relationship was not statistically significant [F(1, 293) = 3.207, p = .074]. The relationship between the average time of the PIR sensor to respond to the laser and the distance between the laser diode and the PIR sensor can be seen in Figure 3.4.

3.4 Final Device

3.4.1 Effectiveness of Light Sensor & Threshold

During this phase of testing, the light sensor threshold was set to a light intensity value of 175 lux, determined by the earlier phases of the study. This threshold proved accurate in the testing stage, successfully triggering the device when office lighting conditions fell below the threshold. The consistency of the light sensors' performances under varying lighting conditions confirms their reliability and suitability for integration into the final device.

3.4.2 PIR Sensor Interaction

Initially, the device successfully activated a PIR sensor in tests conducted within a range of 10 up to 40 centimetres. However, when the device was placed in the actual office setting, the IR laser diode's effectiveness in deceiving the PIR sensor decreased. The laser failed to activate the PIR sensor consistently when the distance between the laser and the sensor exceeded 40 centimetres. Despite various adjustments to the positioning of the device, the IR laser was not able to reliably deceive the office's PIR sensor at distances greater than 40 centimetres. As placement within 40 centimetres is not possible in the current office environment, the device is ineffective.

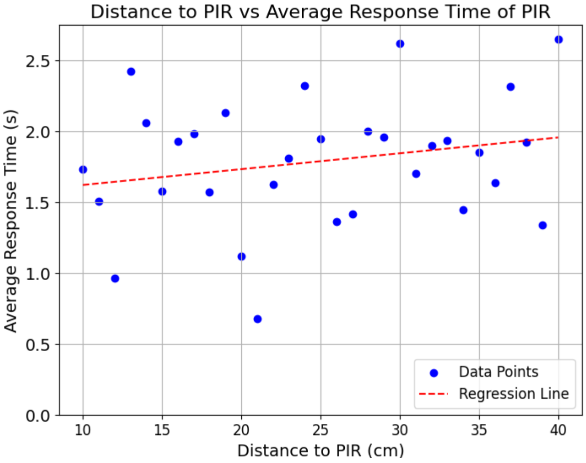

Figure 3.4: The average response time of IR laser detection of the PIR sensor as the distance with the laser increases. Measurements were taken at intervals of one starting from 10 centimetres, with ten trials at each interval. The regression line indicates the relationship between the distance of the laser diode to the PIR sensor and the time it took for the sensor to detect the laser.

4 Discussion

4.1 Light Sensor Performance

The comparison between the GL5528 and GL5537 light sensors demonstrated their reliable and consistent performance detecting light changes within an office environment. The GL5537 sensor portrayed a slightly higher sensitivity than the GL5528, making it potentially more suitable for applications requiring precise light detection capabilities. However, both sensors performed adequately, indicating their potential for integration into the final device. The TEMT6000X01 sensor module could not be successfully attached to the breadboard and thus produced inconsistent data. THerefore, it was excluded from further consideration.

4.2 PIR sensor & Laser Effectiveness

The primary objective of the PIR sensor deception phase was to evaluate the effectiveness of the ADL-78051TL infrared laser diode in triggering the sensor from various distances. The results showed successful activation of the sensor up to 40 centimetres, after which the accuracy of the PIR sensor decreases.

The regression analysis revealed a statistically significant but weak relationship between the distance of the laser to the sensor and the amount of movement required by the laser for detection. Simultaneously, an insignificant finding occurred for the weak linear relationship between the response time of laser detection by the PIR sensor and the distance of the laser to the sensor.

Despite the significant finding, the low R-squared value indicates that other variables not included in this study may influence the outcomes. The accuracy limit beyond a distance of 39 centimetres could be related to the physical limitations of the sensor and the effectiveness of the laser, rather than the characteristics of the changes themselves. The practical implications of these findings may limit the use of this specific setup in environments where long-range deception is necessary.

4.3 Limitations and Future Research

The development and initial testing phases of the device have demonstrated promising results, but several limitations and future developments are to be discussed. Firstly, the movement of the laser was manually controlled during the experiments, which is not a feasible solution for the final device. Manual control of the laser diode is impractical for real-world applications. The intended solution requires a mechanism to automate the movement of the laser. Given the results, the necessary average amount of movement can reach up to 10 centimetres. Therefore, when considering the final device in practice, the average amount of necessary movement for the laser to be detected may conflict with the design requirements specified by the clients. Future solutions must incorporate an automated system to control the amount of movement of the laser consistently, ensuring that the laser remains effective within the intended setting. Future research could address the following research question: What are the optimal design specifications for an automated system that controls an IR laser's movement in effectively triggering a PIR sensor?

The second key limitation is the reduced effectiveness of the IR laser diode at distances exceeding 39 centimetres. Expanding the laser with lenses may enhance the device's capability. By attaching lenses, the laser's beam can be focused or spread to better match the required coverage area for triggering a PIR sensor. Moreover, considering a multidimensional approach by incorporating a second laser could further enhance the effectiveness of the setup. By utilizing two lasers, the PIR sensor can be triggered from multiple angles and distances, which can improve the accuracy of the device. It could also increase reliability by reducing the chances of false negatives, which is when the PIR sensor fails to detect a single laser. An example research question for this type of investigation could be: Is the addition of a second laser more effective than optimizing the movement of a single laser in triggering PIR sensors?

On the other hand, further investigation into other variables that might influence the effectiveness of the laser and PIR sensor interaction is recommended. Factors may include characteristics of the PIR sensor, such as sensitivity or delay, that could play a role in the performance of the system. This leads to the following research question: What characteristics of PIR sensors most significantly affect the interaction with IR laser diodes?

4.4 Conclusion

In conclusion, this study successfully developed and tested a low-cost robotic extension to occupancy-based lighting control systems, demonstrating the potential to improve the detection of static users. While the current setup shows promise, further research and optimization are necessary to address the identified limitations and enhance the device's effectiveness. The final device will need an automated mechanism to control the movement of the laser. Besides, there is a possibility that by integrating additional components, such as lenses to increase transmission or multiple lasers, the final device could better meet the requirements in office environments, enhancing both energy efficiency and user comfort. Additionally, future research should investigate the characteristics of PIR sensors that could influence the interaction with IR laser diodes, aiming to perfect the overall system. The continued exploration of these design considerations and effectiveness by integrating robotic extensions in occupancy-based lighting control systems holds promise for enhancing user comfort in office environments.

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A Appendix

Sensor		GL5528		GL5537	
Light Status (lux)		ON	OFF	ON	OFF
Left shelf	Mean	752.22	0	582.08	0
	Standard Deviation	49.36	0	70.25	0
	Maximum	787	0	624	0
	Minimum	643	0	432	0
	Mean Change Percentage From ON to OFF	100		100	
Desk	Mean	949.35	68.4	744.69	22.16
	Standard Deviation	64.95	61.72	92.06	40.91
	Maximum	1083	160	914	105
	Minimum	887	9	666	0
	Mean Change Percentage From ON to OFF	92.80		97.02	
Right shelf	Mean	512.90	5.16	295.43	0
	Standard Deviation	83.07	6.90	36.44	0
	Maximum	592	21	338	0
	Minimum	355	0	237	0
	Mean Change Percentage From ON to OFF	98.99		100	

Table A.1: Average, standard deviation, maximum, minimum, and mean change percentage of the light intensity values of sensors GL5528 & GL5537 averaged across different days, measured at three different locations.