JOURNAL LA MULTIAPP

VOL. 07, ISSUE 03 (594-607), 2026
DOI: 10.37899/journallamultiapp.v7i3.3139

Development of an Automated Infrared Therapy System Based on MLX90614 Sensor for Muscle Pain Treatment

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Article Info

Article history:
Received 25 February 2026
Received in revised form 6 April 2026
Accepted 5 May 2026

Keywords:
Temperature Control System
MLX90614 Infrared Sensor
HC-SR04 Ultrasonic Sensor
Proportional Controller
PWM

Abstract

This study aims to design and evaluate an automatic infrared therapy system capable of maintaining temperature stability within a safe and controlled range. The system utilizes a non-contact infrared temperature sensor MLX90614, an ultrasonic distance sensor HC-SR04, an Arduino Uno microcontroller, and an infrared lamp regulated by a pulse width modulation (PWM) signal. Temperature control is implemented using a proportional control (P-Control) method, while sensor data is processed using a moving average filter to reduce measurement noise. Experimental testing was conducted by comparing system responses without control and with P-Control at three distance variations, namely 15 cm, 30 cm, and 45 cm. The results show that the uncontrolled system produced a temperature deviation of ±1.8°C, while the implementation of P-Control reduced the deviation to ±0.6°C at a setpoint of 45°C. However, the achieved average temperature varied depending on distance, with values ranging from 35.27°C to 42.61°C across all test conditions. These results indicate that the application of P-Control combined with a moving average filter is effective in improving temperature stability, although the heating performance is influenced by the distance between the sensor and the object. This system demonstrates potential for safer and more controlled infrared therapy applications.

Introduction

Muscle pain is a common health issue that can be experienced by people of all age groups and across different types of occupations (Miranda et al., 2010; Parsons et al., 2007). This condition is typically associated with musculoskeletal disorders caused by excessive physical activity, poor posture, repetitive movements, or certain chronic illnesses. The Global Burden of Disease report indicates that musculoskeletal disorders significantly contribute to an increase in functional disability and reduce an individual's quality of life and productivity (Al-Ajlouni et al. 2024; Safiri et al., 2021; Sebbag et al., 2019; Smith et al., 2014; Cieza et al., 2020).

ISSN: 2716-3865 (Print), 2721-1290 (Online)

One commonly used non-pharmacological therapy for reducing muscle pain is infrared therapy. This method uses heat radiation to improve local blood flow, relax muscles, and speed up the recovery of areas that are tense or inflamed (Arianto & Widodo 2022; Lusiana et al., 2022; Ibadillah et al. 2022). Several studies indicate that infrared therapy is low risk, does not cause pain, and can be used in healthcare facilities or independently at (Tanjung et al. 2022.

However, most of the available infrared therapy devices still rely on manual settings for heat intensity and exposure duration (Lubkowska & Pluta, 2022; Tsagkaris et al., 2022). This situation makes it difficult for users to maintain a stable temperature and may lead to discomfort when the temperature exceeds the safe limit for the skin. Some studies also highlight that improper temperature settings can cause irritation or mild burns, especially when used for long periods without adequate monitoring (Negara et al. 2023; Shahid et al., 2025). In addition, the reliance on manual settings makes the therapy results heavily dependent on the user's experience.

Efforts to develop infrared therapy devices based on microcontrollers have been made, such as using Arduino or STM32 (Ibadillah et al. 2022). However, most of these devices are not yet equipped with sensors to measure skin temperature directly and in real-time. This caused the device to be unable to adjust the heat intensity according to temperature changes during the therapy process. Some studies have begun using the non-contact infrared sensor MLX90614 for body temperature measurement (Tanjung et al. 2022; Hariyanto et al., 2025; Mutaqi, 2025), but they are still limited to closed-loop monitoring systems without automatic control.

On the other hand, automatic control methods such as Proportional–Integral–Derivative (PID) have been widely used in various temperature control systems because of their ability to maintain stable conditions and respond quickly to changes. The use of PID control has been shown to be effective in medical devices such as blood warmers and other heating systems (Santoso et al. 2023; Jamil et al., 2022; Khan et al., 2018; Sharma & Singh, 2021; Pham et al., 2022).

This technique is also applied in various other fields, such as food product temperature storage, industrial systems, robotics, and home automation systems (Arifuddin et al. 2024; Wisaksono & Mokhtar, 2022; Wisaksono & Pratama, 2023; Negara et al. 2023; Alamsyah et al. 2023; Saickoni et al. 2025). This method demonstrates good stability in temperature control across a wide range of systems. However, the application of PID in infrared therapy devices that include non-contact skin temperature measurement and focus on user safety has not been extensively reported in previous research (Zhao, Y., & Bergmann, 2023; Yang et al., 2020; Rodríguez-Cobo et al., 2023; Tan et al., 2025).

Advancements in embedded systems and non-contact sensors offer significant opportunities to enhance the security and effectiveness of infrared therapy (AlZubaidi et al., 2018; Abdulhussain et al., 2025). The MLX90614 sensor is capable of measuring skin temperature in real time without direct contact, making it more hygienic and comfortable to use (Hariyanto et al., 2025; Tanjung et al. 2022; Panja et al., 2025). The temperature data collected can be processed by the Arduino Uno microcontroller to automatically regulate infrared radiation through a power controller.

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By using a closed-loop PID control system, the therapy temperature can be maintained within a safe and stable therapeutic range (Afiah et al. 2025; Arifuddin et al. 2024; Noor, 2026). Based on this background, this research aims to design and implement an automatic infrared therapy system using the MLX90614 sensor and PID control to enhance user comfort and safety compared to conventional devices that still rely on manual adjustments.

Methods

This study employed an experimental method with a research and development approach. This method was chosen because the research focused on the design, implementation, and performance testing of an automated infrared therapy device based on a closed-loop temperature control system. The research process included stages such as system design, hardware assembly, software development, system integration, and measurable device performance testing.

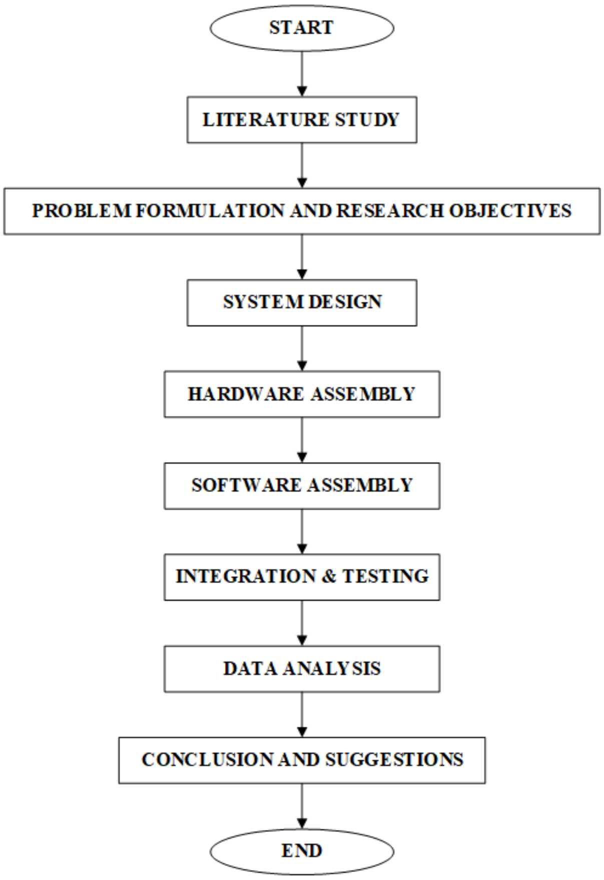

Figure 1. Research Procedure

System Design

The infrared therapy system uses a closed-loop control concept, where skin surface temperature is used as feedback to automatically adjust the intensity of infrared light. A non-contact temperature sensor called the MLX90614 is used to read the object's temperature in real time. This data is processed by an Arduino Uno microcontroller to generate a control signal in the form of Pulse Width Modulation (PWM), which controls a TRIAC-based AC dimmer module. Infrared light serves as the primary actuator for generating therapeutic heat.

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This approach is designed to maintain the therapeutic temperature within a safe range of 41 to 45 degrees Celsius. Temperature data is filtered using a 5th-order moving average filter to reduce noise from infrared sensor measurements.

System Block Diagram

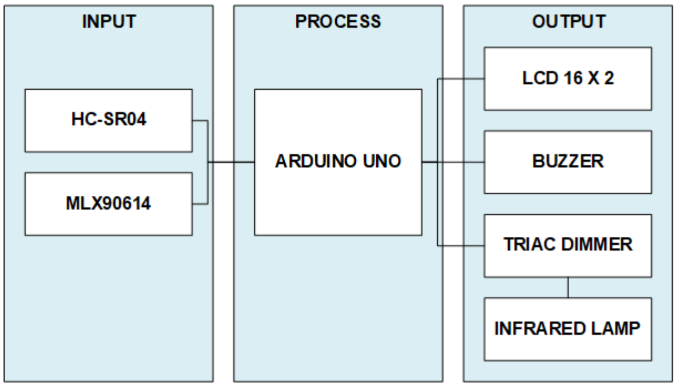

Figure 2. Block Circuit Diagram

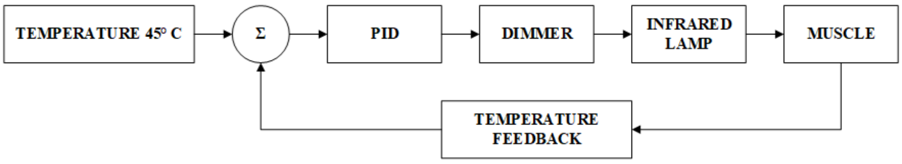

Figure 3. Block Diagram of PID System

The system block diagram includes an MLX90614 temperature sensor as input, an Arduino Uno as a processing unit, a PID control algorithm as a controller, an AC dimmer module as a power regulator, and an infrared lamp as an output. The sensor reads the skin surface temperature, then sends the data to the microcontroller to compare it with the setpoint value. The difference between the actual temperature and the setpoint is used as input for the PID algorithm to determine the change in the PWM value, which automatically controls the intensity of the infrared lamp. This structure allows the system to respond to temperature changes quickly and stably.

Hardware Design

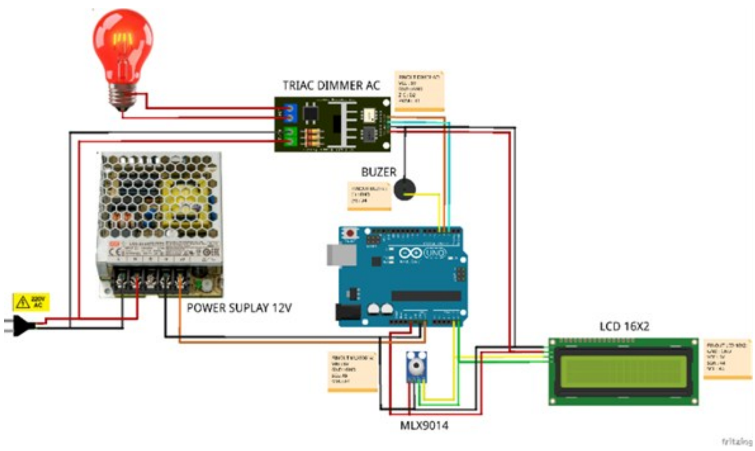

Figure 4. Circuit Design

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The hardware system includes an Arduino Uno R3, an MLX90614 sensor, a TRIAC-based AC dimmer module, a 150W infrared lamp, a 16x2 LCD display, a buzzer, and a power supply. The MLX90614 sensor is connected to the Arduino via I2C communication to obtain high-resolution temperature data. The AC dimmer module is used to control the amount of electrical power sent to the infrared lamp based on a PWM signal from the microcontroller. The hardware design considers safety aspects, especially the isolation between the low-voltage circuit and the AC voltage.

Software Design

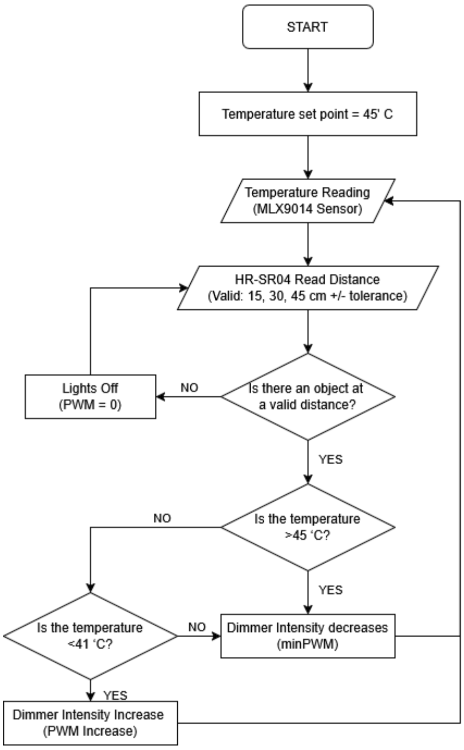

Figure 5. Flowchart

The software was developed using the C programming language on the Arduino IDE, and it includes the initialization of the infrared temperature sensor MLX90614, the ultrasonic distance sensor, the I2C-based LCD display, and the system control parameters. The system reads the object's temperature and distance at regular intervals, every minute, and then processes the data using a moving average filter with a window size of 3 samples to reduce sensor reading fluctuations and improve data stability. The temperature value obtained from filtration is compared with the therapeutic set point of 45°C to determine the temperature error. Temperature control is implemented using proportional control (P-Control) with a proportional gain value (Kp) of 10. The control output is calculated based on the difference between the actual temperature and the setpoint using a proportional approach. The Kp value was obtained by trying different settings until the system response became stable without noticeable oscillations. The calculated result is then converted into an 8-bit Pulse Width Modulation (PWM) signal to control the intensity of the infrared light on the lamp driver, with the PWM value range limited between 0 and 204 (approximately 0–80% duty cycle of the Arduino's 0–255 PWM range) to prevent excessive heating. In addition, the system has a

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security feature that automatically stops the PWM output if the object is outside the 15–50 cm therapy range or if the temperature goes above 45°C, and it also sounds a buzzer to warn when the object is not in the recommended distance range.

Testing Procedure

The system is tested to check how accurate, stable, and responsive the infrared therapy device's control is. The accuracy test of MLX90614 was conducted by comparing the temperature readings against a standard infrared thermometer at distances of 15 cm, 30 cm, and 45 cm. Each test condition is repeated three times to ensure the data is consistent. Sensor data is collected every minute during each test over a specific observation period until the conditions become stable. The temperature values obtained are processed using the mean calculation, and the standard deviation is determined to assess the data spread and measurement error relative to the reference device. Stability testing of temperature is done by running the system at a set point of 41 to 45 degrees Celsius and observing how stable the temperature remains during the testing process. The PID control response test is done to find out how long it takes for the system to react and how much it goes beyond the desired level when there is a change in conditions. The entire implementation was conducted under controlled environmental conditions, including room temperature, fixed and vertical sensor position relative to the object, distance, and the characteristics of the tested object. All the test data is recorded and analyzed to evaluate the performance and safety of the automatic infrared therapy system.

Results and Discussion

This section presents the results of testing an automated infrared therapy system focusing on evaluating temperature stability using PID control, as well as the impact of distance changes on system performance.

Temperature Stability Test Results Without and With PID

This test was conducted to assess the impact of implementing the PID control method on temperature stability in therapy. The system was tested under two conditions: without PID control and with PID control, with the same temperature setpoint. Observed parameters included the average temperature and the magnitude of temperature deviation during the test.

Table 1. Comparison Graph of Temperature Response Without PID and With PID

No.	Without PID			PID + Moving Average Filter		
	I	II	III	I	II	III
0	27.10	28.90	31.30	33.49	31.79	23.83
1	39.90	33.60	31.50	44.55	39.54	36.07
2	40.00	33.90	36.00	44.90	45.00	36.71
3	36.00	34.00	43.10	44.93	44.95	37.27
4	27.90	34.00	43.20	44.95	44.74	37.78
5	32.20	34.10	31.80	42.11	44.73	38.10
6	40.30	42.50	31.80	44.98	45.00	38.46
7	28.20	42.60	43.30	39.69	41.24	38.74
8	32.50	29.80	32.00	44.90	41.44	39.07
9	40.80	29.80	43.30	44.96	43.08	39.94
10	32.60	30.00	36.30	43.79	39.46	39.57

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11	32.80	34.50	43.10	44.99	44.42	39.75
12	28.60	41.70	36.20	38.86	39.63	39.99
13	33.00	30.20	31.80	40.73	41.05	40.15
14	28.90	34.90	36.10	39.65	41.77	40.32
15	41.30	30.50	31.80	40.74	41.17	40.51
16	29.10	42.10	31.80	42.09	41.88	40.70
17	41.40	30.70	31.60	44.98	42.38	40.77
18	33.50	42.20	43.20	41.74	39.77	40.93
19	29.20	30.80	43.10	38.82	45.38	41.03
20	41.50	30.80	31.90	40.07	39.79	41.16
21	29.40	42.40	31.90	44.96	39.81	41.34
22	29.40	42.60	32.00	41.14	43.05	41.50
23	41.60	39.80	31.90	38.98	44.63	41.69
24	29.50	31.20	31.90	38.96	42.40	41.78
25	41.60	31.40	36.20	39.67	42.37	41.88
26	33.80	42.80	31.90	41.78	40.05	41.92
27	23.30	35.90	43.10	44.96	39.84	42.07
28	28.40	35.90	36.20	44.96	39.86	42.17
29	28.20	35.90	40.30	45.01	44.92	42.37
30	42.00	31.50	36.20	39.76	39.42	42.43

Table 1 shows that the use of PID control significantly reduced temperature deviation compared to systems without PID. The PID-controlled system demonstrated better temperature stability and maintained the therapeutic temperature close to the set value. This aligns with the basic principles of PID control, which aim to reduce errors and minimize temperature variations through feedback mechanisms.

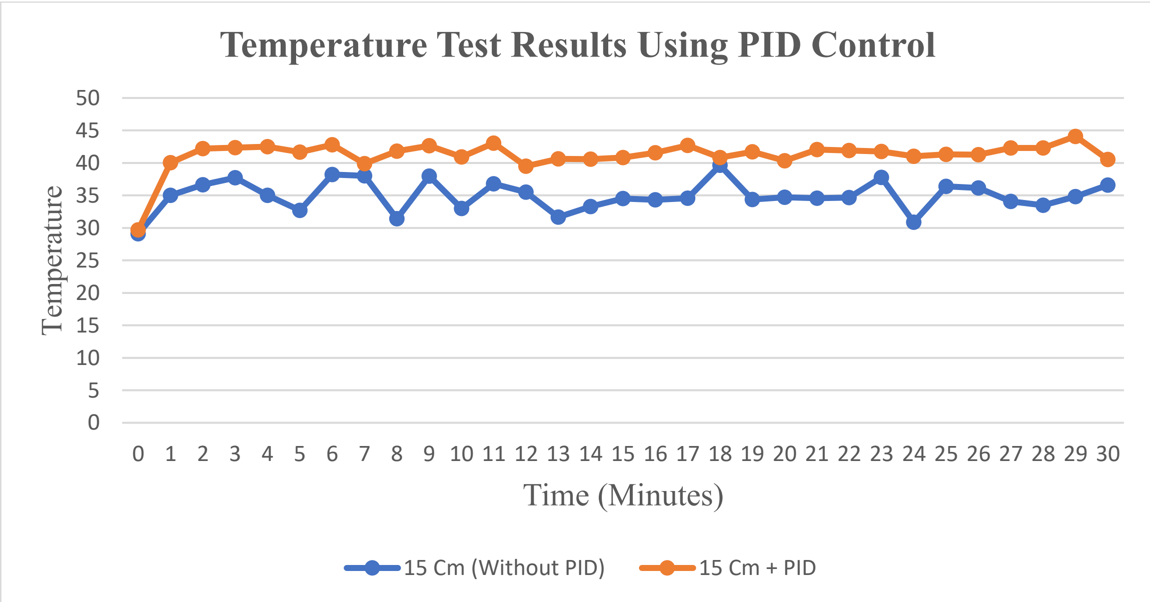

Figure 6. Graph of Temperature Test Results Using PID Control

According to Figure 6, the system without control mechanisms shows relatively large temperature fluctuations and a tendency for temperature to rise beyond the set value before

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reaching a stable condition. This condition shows that heating without a control system cannot keep the temperature at the set point consistently. On the other hand, using proportional control results in a more directed temperature response with better system dynamics characteristics. This can be observed from the transient response parameters, such as rise time, settling time, overshoot, and steady-state error. With the addition of a P controller, the time it takes for the system to reach a value close to the desired set point (rise time) becomes shorter, and the time needed for the system to reach a stable condition (settling time) is also faster compared to a system without control.

Even so, the system's response still shows an overshoot, which is when the temperature goes beyond the set point before finally settling down. This phenomenon is not only caused by the use of proportional control, but also influenced by several technical factors within the system. One of the main factors is the relatively high proportional gain value, which causes the system to respond to errors in a strong and fast way. In addition, the thermal inertia of the heating medium causes the accumulated heat to continue raising the temperature even when the control signal starts to decrease. Another factor that also affects this is the delay in the temperature sensor reading, the sampling interval in the digital control system, and the dynamic response characteristics of the infrared light, which cannot change instantly. On the other hand, although the P controller can speed up the system response, this method still allows for the occurrence of steady-state error, which is a small difference between the actual temperature and the set point in a steady state. Therefore, the observed system characteristics are the result of the interaction between the controller tuning parameters and the thermal dynamics of the heating component used.

Table 2. Comparison of Temperature Stability Test Results Without PID and With PID

No.	Temperature (°C)								
	15Cm			30 Cm			45 Cm		
	I	II	III	I	II	III	I	II	III
0	33.49	31.79	23.83	31.57	25.35	25.17	25.95	25.53	33.19
1	44.55	39.54	36.07	34.67	35.38	36.63	37.51	40.01	42.74
2	44.90	45.00	36.71	29.95	35.93	37.68	39.21	41.02	41.12
3	44.93	44.95	37.27	30.64	36.30	38.38	40.07	41.69	41.89
4	44.95	44.74	37.78	30.77	36.69	38.65	40.90	41.98	42.50
5	42.11	44.73	38.10	31.03	36.87	38.94	41.41	42.97	42.61
6	44.98	45.00	38.46	31.12	36.65	38.96	42.17	42.74	42.73
7	39.69	41.24	38.74	31.41	36.24	39.13	41.77	42.71	42.74
8	44.90	41.44	39.07	31.38	36.37	39.41	42.36	42.77	42.78
9	44.96	43.08	39.94	31.58	36.14	39.25	42.33	43.11	42.72
10	43.79	39.46	39.57	31.64	36.21	39.24	42.05	43.23	42.82
11	44.99	44.42	39.75	31.71	36.17	39.31	42.16	42.92	43.00
12	38.86	39.63	39.99	31.80	36.29	39.42	42.04	42.90	42.82
13	40.73	41.05	40.15	31.89	36.16	39.33	40.91	42.81	42.99
14	39.65	41.77	40.32	32.00	36.27	39.39	40.11	43.16	42.90
15	40.74	41.17	40.51	32.01	36.35	39.42	40.13	43.75	42.87
16	42.09	41.88	40.70	36.96	35.98	39.59	40.83	43.90	42.74
17	44.98	42.38	40.77	36.70	35.72	39.58	35.10	43.94	42.71
18	41.74	39.77	40.93	36.75	35.90	39.56	39.47	44.05	42.83

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19	38.82	45.38	41.03	37.00	36.08	39.37	34.52	44.32	42.64
20	40.07	39.79	41.16	36.88	36.00	39.54	38.73	44.32	42.80
21	44.96	39.81	41.34	37.03	35.68	39.56	39.22	43.38	42.70
22	41.14	43.05	41.50	43.31	35.77	39.56	36.40	43.70	42.85
23	38.98	44.63	41.69	43.41	35.70	39.35	39.31	44.08	42.86
24	38.96	42.40	41.78	43.53	35.54	39.59	32.53	44.04	43.11
25	39.67	42.37	41.88	43.42	29.11	39.49	40.54	44.03	42.94
26	41.78	40.05	41.92	43.41	27.07	39.26	40.06	44.32	43.10
27	44.96	39.84	42.07	43.52	35.91	39.42	40.35	44.09	43.16
28	44.96	39.86	42.17	43.55	36.19	39.21	40.32	42.93	43.09
29	45.01	44.92	42.37	43.64	36.62	39.48	41.11	44.10	43.21
30	39.76	39.42	42.43	43.64	36.78	39.30	38.26	42.50	43.16

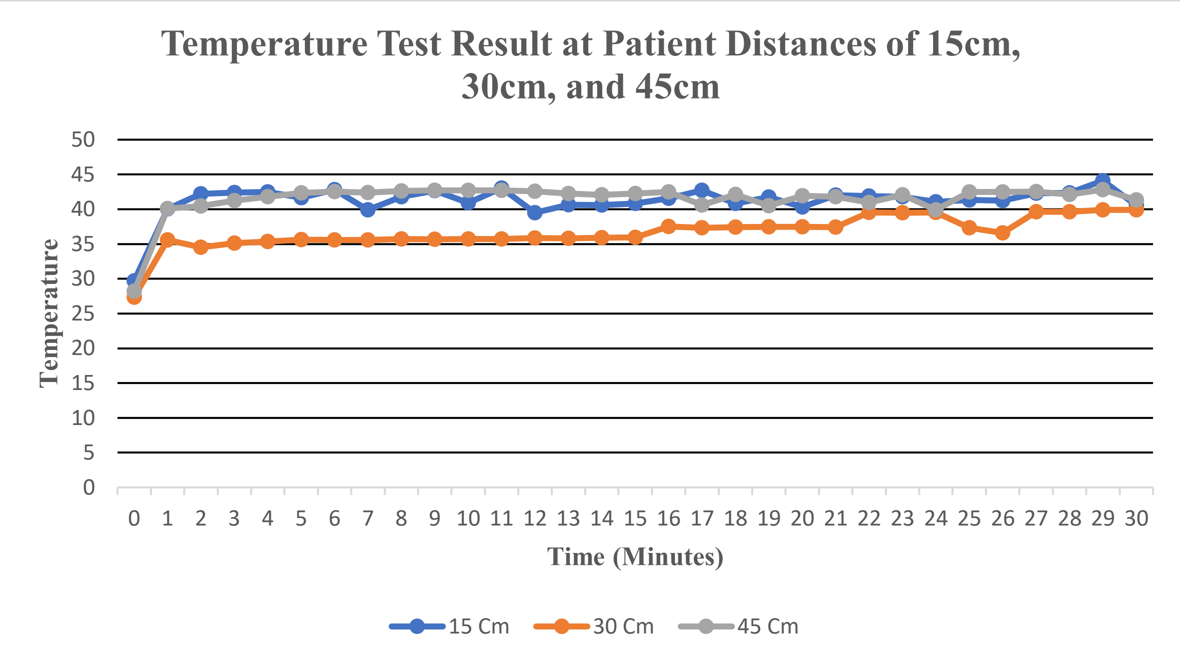

Figure 7. Graph of Temperature Test Results at Patient Distances of 15cm, 30cm and 45cm

The results in Figure 7 show that the temperature control system remains stable within the effective distance range of 15 to 45 cm. During this period, the system was still able to maintain a temperature close to the reference point with a fairly consistent response. Initial low temperature readings are due to system warm-up conditions before reaching thermal equilibrium. However, at greater distances, the temperature response becomes less stable, shown by a slower rate of temperature rise, because the intensity of infrared energy received by the object decreases. This is related to the decrease in radiation energy as distance increases, causing the heating process to slow down and become less responsive to control changes. On the other hand, at closer distances, the rate of temperature increase becomes higher because the amount of radiation energy received is greater, so the system tends to heat up more quickly. This situation, along with the heat buildup in the heated object, causes the temperature to keep rising even though the control signal has decreased. As a result, a more significant overshoot occurs, which is not only influenced by the proportional control characteristics but also by the thermal dynamics and energy accumulation within the system.

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Table 3. Summary of Mean Temperature and Standard Deviation

No.	Distance	Mean Temp	Std Dev
1.	15 Cm (Trial I)	42,13	2,91
2.	15 Cm (Trial II)	41,76	2,80
3.	15 Cm (Trial III)	39,68	3,41
4.	30 Cm (Trial I)	36,06	5,29
5.	30 Cm (Trial II)	35,27	2,76
6.	30 Cm (Trial III)	38,72	2,59
7.	45 Cm (Trial I)	39,28	3,44
8.	45 Cm (Trial II)	42,61	3,33
9.	45 Cm (Trial III)	42,46	1,77

Figure 8. Device Implementation on Patient Area

Hardware Circuit Implementation

The infrared therapy hardware system was built according to the design specified in the research methodology. The device consists of an MLX90614 non-contact temperature sensor, an Arduino Uno microcontroller, a TRIAC-based AC lighting module, an infrared lamp, an LCD display for information, a buzzer for warning signals, and a supporting power source.

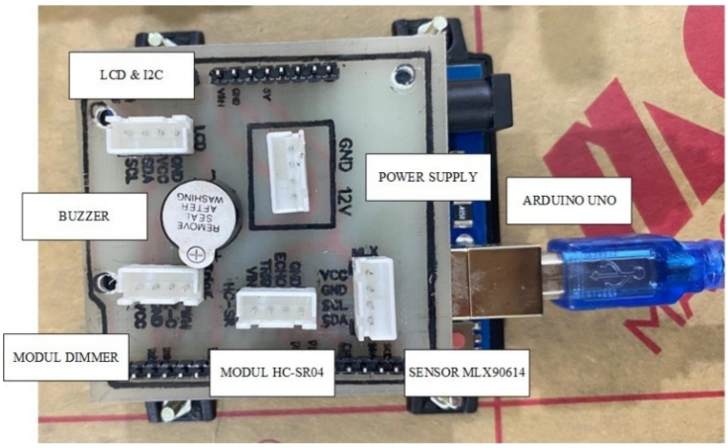

Figure 9. Infrared Therapy System Hardware Circuit

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This implementation allows the system to directly measure temperature and automatically adjust the intensity of the infrared lamp. Integrated components work well together and help maintain the right temperature settings for the therapy needs.

Conclusion

Based on the implementation, testing results, and performance evaluation, it can be concluded that the automatic infrared therapy system using the MLX90614 sensor and P-Control temperature controller combined with a moving average filter is capable of significantly improving the stability of the therapy temperature compared to a system without control. Using P-Control results in a smoother temperature response, reduces fluctuations, and keeps the temperature close to the setpoint within the tested range, thereby improving user safety and comfort. The system integrates hardware and software that work together efficiently to adjust the intensity of infrared lights based on real-time temperature feedback. However, the use of P-Control still results in a small steady-state error and overshoot, indicating the need for future implementation of full PID control. This study still has some limitations, such as environmental factors like surrounding temperature and airflow that are not fully controlled, which could potentially affect the measurement results and system response. Therefore, further development should include adding integral and derivative control components to improve accuracy, applying more adaptive PID tuning methods, and conducting additional clinical testing in real-world usage conditions over a longer period to more thoroughly evaluate the therapy's effectiveness.

Acknowledgment

The author acknowledges the support and facilities provided by the Muhammadiyah University of Sidoarjo during the research process. The author also thanks the supervisors and laboratory staff for their guidance and technical assistance. Appreciation is also extended to all parties who contributed to the completion of this research.

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