Design and Calibration of a Low-Cost, 3D-Printed, IoT-Enabled Non-Contact Infrared Thermometer with Wireless Feedback for Remote Health Monitoring

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Abstract
Infrared thermometers are non-contact devices that measure temperature by detecting infrared radiation emitted from an object's surface. These devices offer rapid, accurate readings, but challenges such as environmental interference and calibration issues persist. The study aimed to design and calibrate a low-cost 3D printed, IoT-enabled non-contact infrared thermometer with wireless feedback. The main components used to develop the device include the MLX90614 infrared temperature sensor for accurate non-contact temperature readings, an ESP32 microcontroller for data processing and wireless connectivity, and a SIM800L GSM module enabling SMS notifications. The ESP32 was programmed using the C programming language in Arduino IDE. The thermometer's casing was developed using 3D printing technology based on a user-centered approach that enhances ergonomics and durability while significantly reducing production costs. Comparative analysis of the 3D printed infrared thermometer and a standard commercial infrared thermometer before and after calibration showed a significant reduction in Root Mean Squared Error (RMSE) from 2.89 °C to 0.21 °C. *The Mean Absolute Error (MAE) reduced significantly from 2.8 °C before calibration to 0.17 °C after calibration.* The results revealed comparable performance of both IR thermometers. *The study effectively developed a prototype 3D printed infrared thermometer that combines contactless sensing and wireless transmission of temperature data through SMS and email.*

Keywords: Infrared sensor, Internet of Things, Infrared thermometer, Remote Health Monitoring, and SMS feedback.

1.0 INTRODUCTION

An infrared thermometer is a medical device used to measure surface temperature of an object from a distance. Infrared temperature measurements are widely used in various fields including medical diagnostics, and various industrial applications. The main function of infrared thermometers is to measure the temperature of an object without physically making direct contact with it. This measurement is possible because a physical body with a temperature above absolute zero is capable of producing electromagnetic radiation that is relative to its body temperature (Piccinini *et al.*, 2021).

Since there is no direct contact between an infrared thermometer and a patient, the risk of transmitting infectious diseases using infrared thermometers is highly reduced. With the outbreak of the COVID-19 pandemic, infrared thermometers saw widespread use in screening patients for fever to limit the spread of the disease (Lee *et al.,* 2020; Foster *et al.,* 2021; Hussain *et al.,* 2021; Lai *et al.,* 2022). Other applications of infrared thermometers include climate change and meteorology studies to monitor the temperature of the land's surface (Lahiri *et al.,* 2012), and use at airports to detect febrile travelers in order to prevent them from spreading infectious diseases (Bitar *et al.,* 2009).

However, infrared thermometers have a number of limitations, including inaccuracies due to environmental conditions, ergonomic issues, casing durability, and design issues (Fletcher *et al.,* 2018; Sullivan *et al.,* 2021). The performance of IR thermometers can be affected by environmental factors such as ambient temperature shifts, moisture in the air, or suspended particles like dust and smoke (Spindel *et al.,* 2021). Inaccurate temperature readings can also occur if the variability in the target surface's emissivity is ignored (Chandramohan *et al.,* 2018). A large number of current designs are cumbersome or not ergonomically suitable, which often leads to user discomfort when used for a long time (Wang *et al.,* 2012).

The use of 3D printing in the rapid prototyping of medical devices is on the increase. With 3D printing technology, custom casings can be prototyped to suit specific needs. Additive manufacturing involves the production of objects by layering materials based on digital models (Hossain *et al.,* 2024). A 3D printer utilizes additive manufacturing to produce the desired shape of an object from three-dimensional data (Ngo *et al.,* 2018; Gibson *et al.,* 2015). Abuzairi *et al.,* (2020) designed an infrared thermometer on the wall, which they called iThermowall. It was designed specifically for fever screening in public places with no need for an operator.

The adoption of 3D printing technology in the manufacturing of medical devices is known to improve their aesthetics, accuracy, durability, and usability. In conventional infrared thermometers, no provision is made for real-time remote monitoring of temperature readings and analysis (Nwaneri *et al.,* 2024). Therefore, there is a critical engineering gap in developing an affordable, ergonomic, and smart IR thermometer that overcomes all the drawbacks posed by traditional methods of measuring temperature.

Despite the increasing deployment of IR thermometers, few solutions combine 3D printing with real-time wireless feedback and accurate calibration for resource-constrained environments. The basic idea for the solution is to provide precise, non-invasive temperature measurement, real-time data monitoring, and remote access. The development of a smart 3D printed infrared thermometer is capable of changing the temperature-monitoring features of traditional infrared thermometers for better public health and safety. Therefore, this study aimed to design, fabricate, and evaluate a low-cost, IoT-enabled infrared (IR) thermometer that addresses the limitations of conventional non-contact temperature measurement systems. A conceptual design was first developed to guide the fabrication process. This ensures that both functional and non-functional requirements were met. The device was equipped with wireless communication capabilities to enable real-time transmission of temperature readings to a mobile phone. Calibration of the IR thermometer is an important objective to improve its measurement accuracy and reliability. Finally, the performance of the developed IR thermometer was evaluated against a commercial standard to validate its effectiveness.

2.0 MATERIALS AND METHODS

2.1 Materials

The infrared thermometer was developed using various electronic components and materials. Several factors influenced the choice of the components for this device. Specifically, a component selection matrix was used to select the temperature sensor and the IR thermometer, as shown in Table 1. The matrix five criteria: accuracy, power consumption, cost, availability, and operating range. A weight is assigned to each criterion based on the order of preference. Each temperature sensor was assigned a score for each criterion. The score is multiplied by the weight to give the weighted score. The MPLX90614 sensor has the highest score of 4.4.

Table 1: Component Selection Matrix for Temperature Sensor Selection

Criteria	**Weight**	**MLX90614**		**TMP117**		**MAX30205**	
		Score	**Weighted Score**	**Score**	**Weighted Score**	**Score**	**Weighted Score**
Accuracy (± °C)	0.3	5	1.5	4	1.2	4	1.2
Power Consumption	0.2	4	0.8	5	1.0	4	0.8
Cost (per unit)	0.2	3	0.6	4	0.8	5	1.0
Availability	0.2	5	1.0	3	0.6	4	0.8
Operating Range (°C)	0.1	5	0.5	4	0.4	4	0.4
Weighted Score			4.4		4.0		4.2

Table 2 shows all the components and materials used in developing the device.

Table 2: Major Components, Their Descriptions, and Functions for the IR Thermometer Design

Component	Description	Function
	This is an infrared non-contact temperature sensor with I2C interface	It measures surface temperature from a distance
ESP32 DevKitC	It is a Wi-Fi and Bluetooth-enabled microcontroller.	It is used for data processing, control logic, and wireless connectivity
SIM800L GSM Module	Quad-band GSM/GPRS module with UART interface	Sends SMS notifications for remote temperature alerts
18650 Li-ion Battery (3.7V, 1500mAh)	Rechargeable lithium-ion battery	The battery provides portable power to the device
TP4056 LIPO Charger Module	Battery charging and protection module for 18650 batteries	Safely charges and manages power to the device
0.96-inch OLED Display	Small I2C-connected monochrome display module	Displays temperature readings on-screen
Push Button	Momentary switch	User-triggered measurement activation
On/Off Switch	Toggle switch	Controls overall power supply to the device
Resistors	Fixed resistors	Pull-up for I2C, signal conditioning
Transistors	Signal amplifiers/switches	Drive GSM module or handle switching logic
3D Printed Casing	Custom-designed enclosure using PLA filament	Houses and protects all electronic components
I2C Cables & Connectors	Wiring harnesses	Facilitate electrical connection between components

2.2 Mathematical Modeling and Simulation

In modeling the device, it was done in 3 different phases.

2.3 Device Design

The functional and non-functional requirements for the design of the IR thermometer are shown in Tables 3 and 4.

A. The Thermal Sensing Model (Infrared Radiation)

The infrared sensor is expected to measure the infrared radiation E emitted from a surface. The infrared radiation emitted by the body being measured is proportional to the fourth power of its absolute temperature (Usamentiaga *et al.,* 2014). The emissivity is governed by the Stefan–Boltzmann Law as stated in equation (1):

$$E = \varepsilon\sigma T^4 \quad (1)$$

Where E is the radiated energy (W/m^2)

ε = Emissivity of the surface

σ= Stefan Boltzmann constant = $5.6703 \times 10^{-8} W/m^2K^4$
T= absolute temperature of the object in Kelvin

The Sensor output voltage, V_{out} is linearly mapped from the detected radiation:

$$V_{out} = k_1 E + k_0 \qquad (2)$$

Where k_1 and k_2 are calibration constants.

B. Signal Processing and Calibration Model

After sensing, the ESP32 performs calibration using linear regression to map raw sensor output to reference values. This is necessary because the raw output from the sensor is often inaccurate. Equation (3) shows the relationship between the calibrated temperature, the raw sensor value and the regression coefficients.

$$\mathrm{T_{cal}} = \mathrm{a} \cdot \mathrm{T_{raw}} + \mathrm{b} \qquad (3)$$

Where:
T_{cal} = calibrated temperature
T_{raw} = Raw sensor value
a, b = regression coefficient derived during calibration

C. Wireless Feedback Model

The delay in GSM/SMS transmission can be modeled as:

$$\mathrm{t_{total}} = \mathrm{t_{proc}} + \mathrm{t_{trans}} + \mathrm{t_{net}} \qquad (4)$$

Where:
t_{proc} = ESP processing time
t_{trans} = time to format and send to GSM module
t_{net} = network latency (random variable)
t_{net} ~ N (μ = 1.2s, σ = 0.3s)

Table 3: Functional Requirements

S/N	Requirements	Description
1	Temperature Measurement	The device should be capable of measuring body or object temperature using a non-contact infrared sensor.
2	Real-time Display	The body is required to display the measured temperature on a screen in real-time
3	Wireless Data Transmission	The device should be able to transmit the measured temperature in real-time remotely using IoT protocols.
4	SMS/E-mail Feedback	The system shall send temperature alerts via SMS or email to a configured address or phone number.
5.	Power Management	The device should be powered by a rechargeable low power battery

The non-functional requirements for the design of the infrared thermometer are shown in Table 4.

Table 4: Non-Functional Requirements

S/N	Requirements	Description
1	Accuracy	The thermometer shall measure temperature with an accuracy of ±0.2°C within the human body range.
2	Response Time	The system shall provide temperature readings within 1 second of measurement.
3	Usability	The user interface (screen or app) is required to be usable and user-friendly by non-technical healthcare workers.
4	Portability	The device shall be lightweight (≤250g) and compact for handheld or bedside use.
5.	Aesthetics and Ergonomics	The 3D printed casing should be designed to have good aesthetics and an ergonomic grip.

The computer-aided design (CAD) model of the infrared thermometer is shown in Fig. 1. The figure displays the front, side, and top views of the thermometer, based on the following specifications: length = 150.9 mm, Height = 190.18 mm, and Width = 65.63 mm. A contoured grip is designed for enhanced user comfort and stability. The infrared thermometer CAD model also indicates a circular aperture (Ø12 mm) that accommodates the infrared sensor for accurate temperature readings.

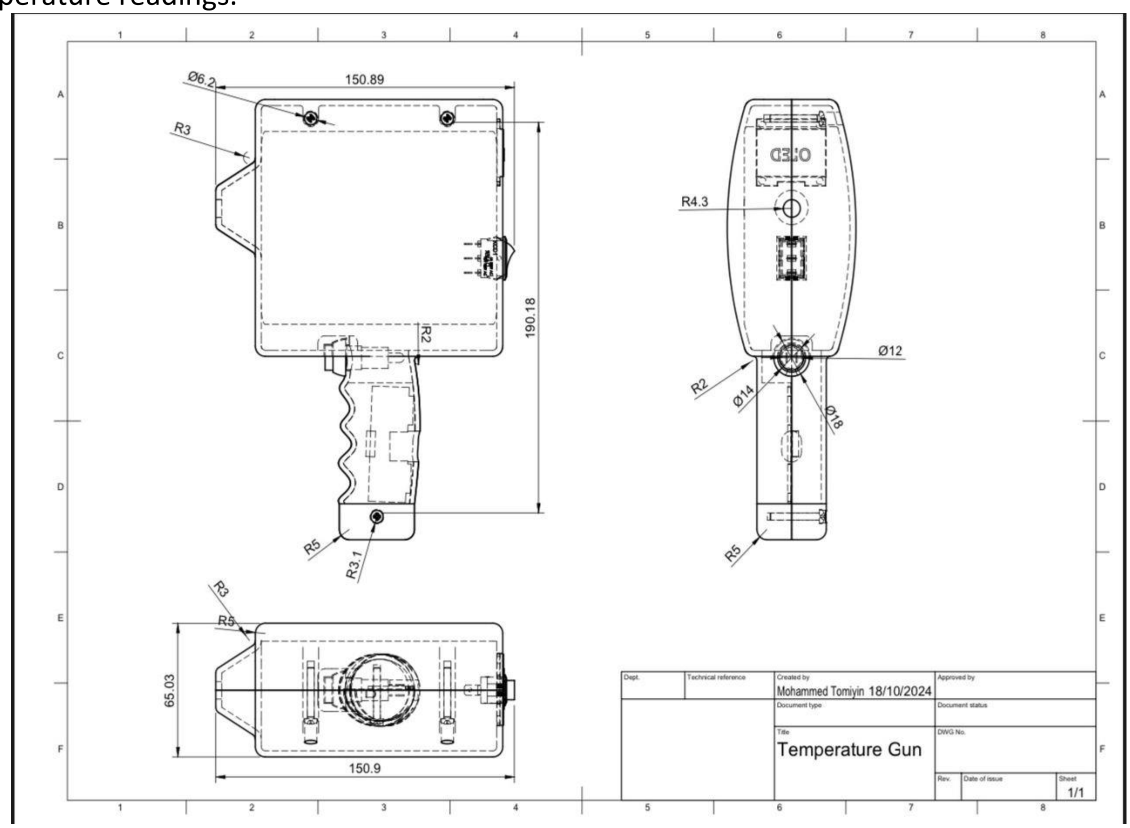

Figure 1: 3D CAD Design of Non-Contact Infrared Thermometer

Figure 2 shows a flowchart that describes the device logic for the 3D Printed IoT Enabled IR Thermometer. When the IR thermometer is powered on, it is used to test the temperature of the patient. If the temperature is equal to or exceeds the threshold temperature of 38°C, the infrared thermometer triggers and transmits an alert remotely to the mobile phone of a physician.

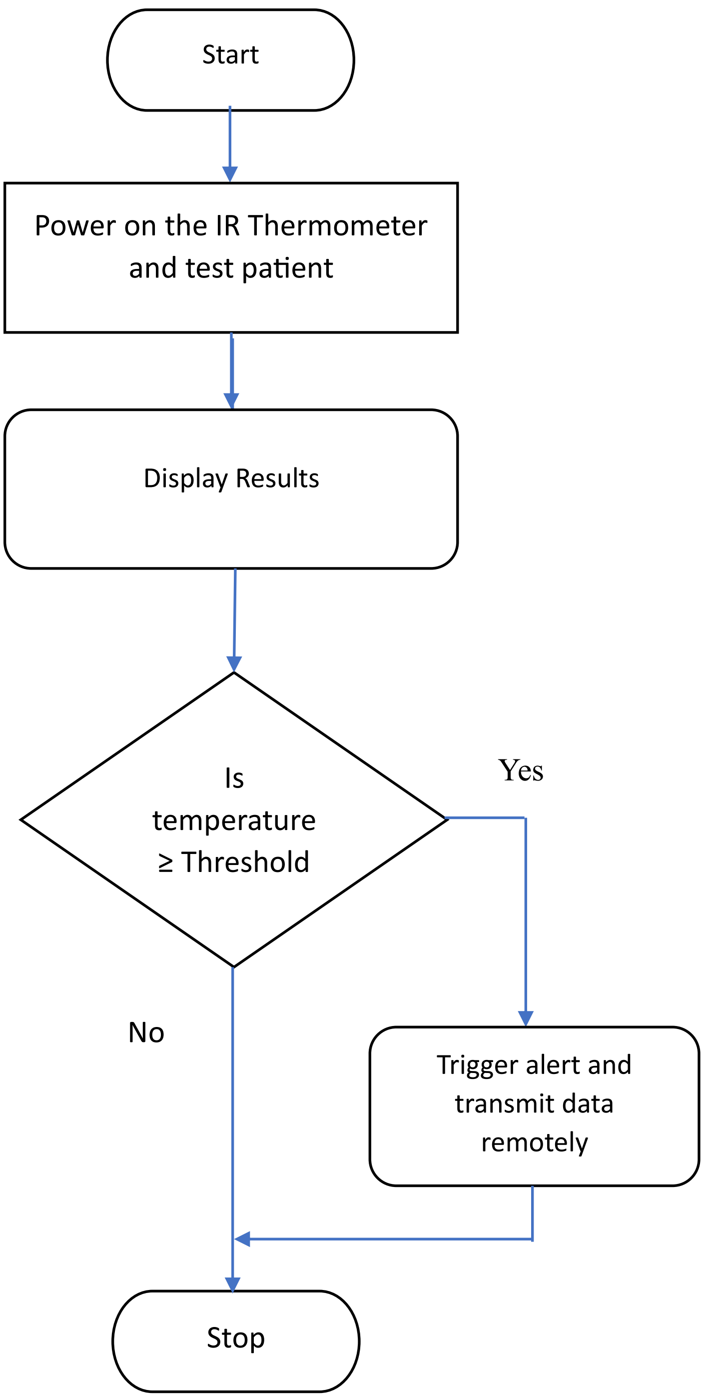

Fig. 2: Device Logic for the 3D Printed IoT Enabled IR Thermometer

A precision design of the infrared thermometer was done using Autodesk Fusion 360 as shown in Figure 3. An ergonomic handle was modeled by the software. The grip is composed of smooth curves and ridges that enhance stability by preventing the device from slipping from the user's hand.

Figure 3: 3D CAD design view of the infrared thermometer

A schematic diagram that shows the working principle is shown in Figure 3. The entire circuit is powered by a 3.7V lithium-ion rechargeable battery and controlled by an on/off switch. When the push button is turned on, current is supplied to the system, making it possible for the MLX90614 infrared temperature sensor to detect the surface temperature from the object being measured. The sensor is interfaced with the ESP32 microcontroller using the I^2C interface. The choice of the ESP32 microcontroller was based on its ability to provide strong processing power, integrated with Wi-Fi and Bluetooth connectivity. ESP32 processes the detected temperature readings and sends them to the OLED screen, which displays the readings. The circuit also contains a 10kΩ pull-up resistor to provide a stable input signal for the button input. The ESP32 microcontroller transmits the results via Wi-Fi to the Wi-Fi of a nearby mobile phone or computer. SIM800L receives the results from ESP32 and sends instant SMS to a remote device.

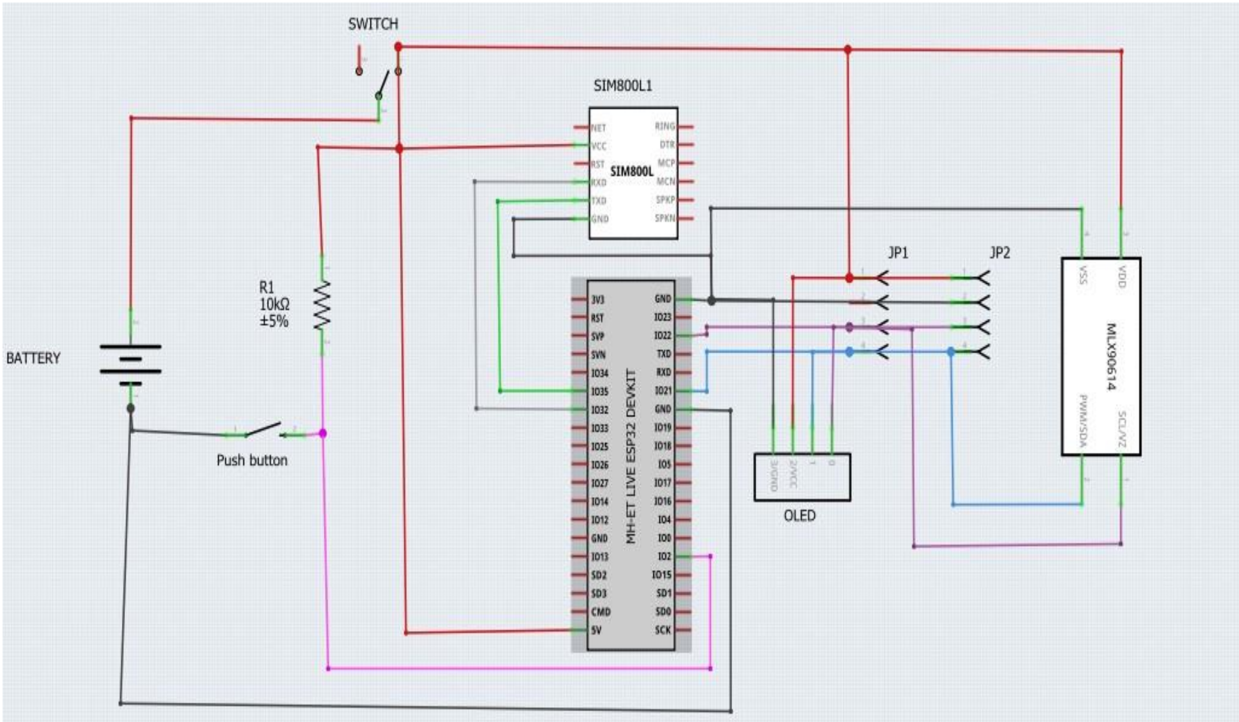

Fig. 4: Schematic Diagram of Infrared Thermometer

The developed IR thermometer was designed and fabricated to meet the functional and non-functional requirements.

2.3 ALGORITHM FOR SIMULATION AND CALIBRATION

An algorithm was proposed to simulate the behavior of the proposed 3D printed IoT-enabled, non-contact infrared thermometer. The algorithm steps for the simulation and calibration of the infrared thermometer are hereby presented.

1. Set Stefan–Boltzmann constant, $\sigma = 5.6703 \times 10^{-8} (W/m^2K^4)$
2. Set surface emissivity, $\varepsilon = 0.98$
3. Set sensor conversion constants:
   Voltage scale factor, $k_1 = 1 \times 10^{-9}\ (V/W/m^2)$
   Voltage offset, $K_0 = 0.01\ V$
4. Generate a sequence of surface temperatures from 30 °C to 40 °C.
5. Convert the temperature values from degrees centigrade to Kelvin

$$T_k = T_c + 273.15$$

6. For each temperature in Kelvin, compute the emitted radiation using the Stefan–Boltzmann Law:

$$E = \varepsilon \times \sigma \times T_k^4$$

7.Convert the radiation values to voltage readings from the IR sensor:

$$V_{out} = k_1 \times E + k_0$$

8.Calibrate Temperature from Sensor Voltage using a linear calibration model

$$T_{cal} = a \times (V_{out} \times 1000) + b$$

9.Model wireless transmission delays as normal distribution

$$Delay \sim N(1.2\ s, 0.3\ s^2)$$

10. Plot calibrated temperature vs true temperature
11. Plot a histogram showing the distribution of simulated SMS transmission delays

3.0 RESULTS AND DISCUSSION

3.1 Simulation Results

Fig. 4 shows a graph of the calibrated simulated temperature versus the true temperature. The dashed green line represents the ideal reference for the calibrated and true temperatures. The ideal reference showed a perfect correlation between the calibrated and true temperatures between 30ºC and 40ºC. These temperature values fall within the temperature range for body surface temperature.

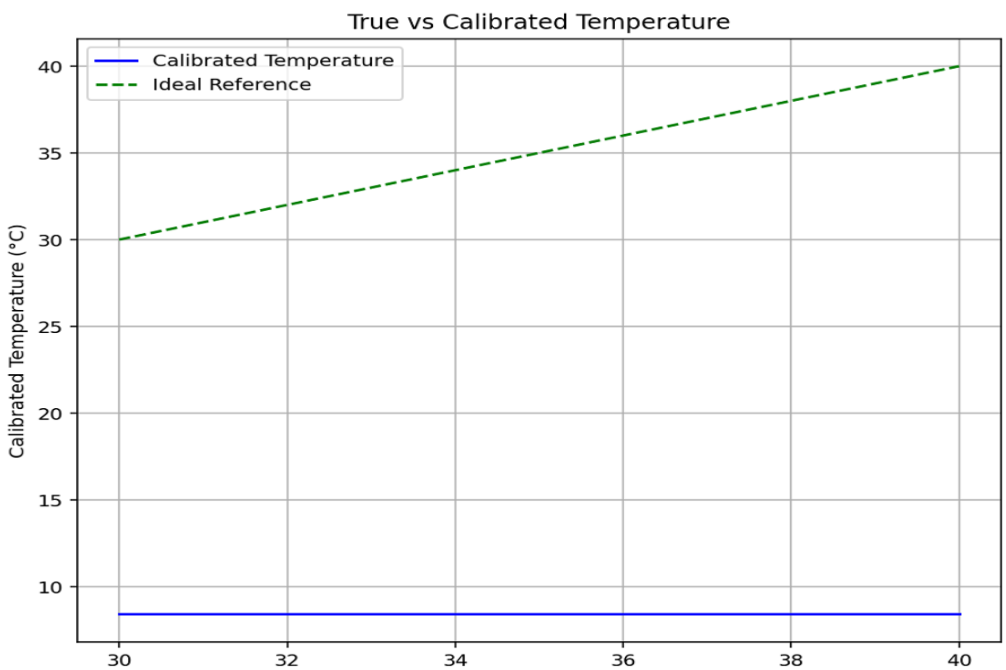

Figure 5: Simulated Temperature Versus True Temperature

Figure 6 presents a histogram showing the distribution of simulated SMS transmission delays of the infrared thermometer. The simulated results indicate an efficient transmission of SMS feedback with a short delay period. The maximum delay of 2.0 seconds has a frequency of 1. While the SMS feedback delays are centered around 1.2 seconds and have minimal variation.

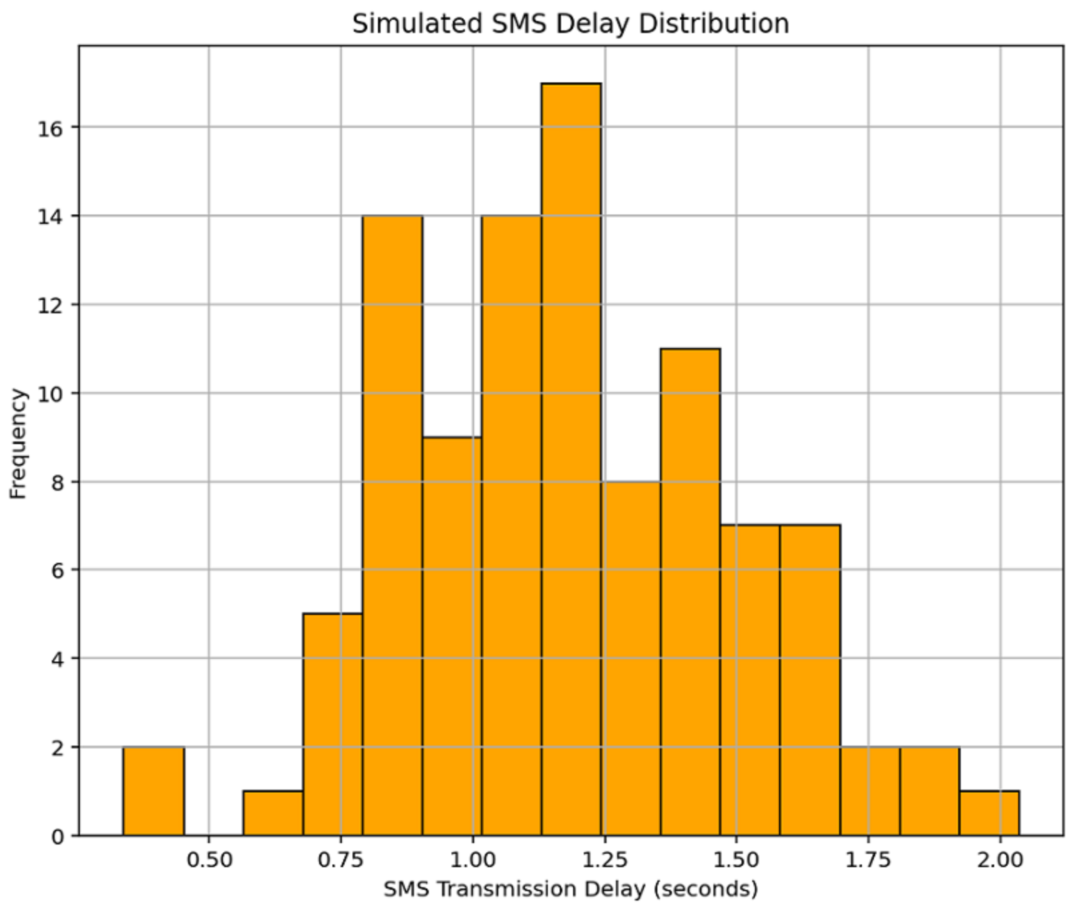

Fig. 6: Histogram showing distribution of simulated SMS transmission delays

3.2 Results of Developed 3D printed Infrared Thermometer Versus Commercial Thermometer

A comparison of the temperature values of our 3D printed infrared thermometer and a commercial infrared thermometer is shown in Table 5. The measurements were made starting at a distance of 5 cm to 20 cm from two different body positions: the forehead and the human arm. Thus, showing the need for the calibration of the device. The object temperature shown in Table 5 was consistently higher for the developed 3D printed thermometer compared to the commercial thermometer. This is apparently due to the non-calibration of the newly developed infrared thermometer. Furthermore, the paired t-Test result between the 3D printed IR thermometer and the commercial one showed a statistically significant difference between the object temperature readings and the commercial device with a t-statistic of 3.86 and a p-value of 0.0062. This suggests that the two devices do not produce the same object temperature readings under the same conditions. It was further observed that the temperature values decreased with increased distance. This is in agreement with previous studies by Nwaneri *et al.,* (2024).

Table 5: Results Before Calibration

Distance (cm)	Subject	Object Temp (3D Developed Device) (^{O}C)	Ambient Temp (3D Developed Device) (^{O}C)	Object Temp (Commercial Product) (^{O}C)	AMBIENT (Commercial Product) (^{O}C)
5	Forehead	34.1	28.4	36.7	29.0
10	Forehead	34.0	28.5	36.4	31.1
15	Forehead	33.9	28.6	36.2	28.9
20	Forehead	33.6	28.9	36.4	30.7
5	Arm	32.6	28.3	36.2	29.4
10	Arm	32.5	28.0	35.8	28.7
15	Arm	32.1	29.7	35.8	28.8
20	Arm	33.8	28.8	35.7	29.8

Despite the variations, the performance of our developed thermometer was relatively stable. Ambient temperature values were measured to gauge the general conditions of the surrounding environment for each reading. This is imperative since infrared thermometers depend on the radiation heat, which is influenced by the surrounding temperature. This is relatively accurate given the proximity in the measured values to those of the commercial product. Table 6 shows the results of the 3D printed infrared thermometer after calibration. Data from the study were analyzed using the Python programming language. Furthermore, the statistical comparison of the 3D thermometers was compared to determine the Root Mean Squared Error (RMSE) and the mean absolute error (MAE) using equations:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(t_p - t_c\right)^2} \quad (5)$$

Where, $t_p = temperature\ of\ proposed\ device$

$\mathrm{t_c} = \mathrm{temperature\ of\ commercial\ device}$

n = Number of tests

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|t_p - t_c\right| \quad (6)$$

Based on the object temperature readings from the 3D developed infrared thermometer and the commercial product**,** the RMSE value of 2.89 °C was obtained. Similarly, the Mean Absolute Error (MAE) of 2.83°C was obtained. This implies that the performance of the thermometer before calibration was relatively inaccurate. The temperature measurements of the device after calibration are shown in Table 6.

Table 6: Results After Calibration

Distance (cm)	Subject	Object Temp (3D Developed Device) (°C)	Ambient Temp (3D Developed Device) (°C)	Object Temp (Commercial Product) (°C)	AMBIENT (Commercial Product) (°C)
5	Human forehead	36.9	28.7	36.7	29.0
	Human arm	36.5	29.3	36.5	29.4
10	Human forehead	36.7	28.8	36.4	29.1
	Human arm	36.3	29.7	36.0	28.7
15	Human forehead	36.5	29.0	36.2	28.9
	Human arm	36.0	30.1	35.9	29.8
20	Human forehead	36.4	28.9	36.4	29.7
	Human arm	35.9	30.2	35.7	29.8

A paired sample t-test was performed to determine if there is a statistically significant difference between readings of both thermometers. Similarly, the Bland-Altman test was used to determine if there is an agreement and bias between the devices. The paired sample t-test results indicated RMSE and MAE of 0.21 °C and 0.17°C respectively. The RMSE reduced significantly from 2.89°C (before calibration) to 0.21°C (after calibration). However, there is no statistically significant difference between the ambient temperature readings of the two devices (t-statistic = 0.195, p-value = 0.8512). This confirms that the performance of the developed 3D printed infrared thermometer is comparable to that of the commercial device. The Bland-Altman plot is shown in Fig. 7. While the X-axis shows the mean temperature of each pair of readings, the Y-axis represents the difference in temperature between the two devices. The graph revealed a mean difference between the two devices of approximately 0.17. This implies that the 3D printed infrared thermometer reads approximately 0.17 °C higher than the standard commercial product. Calibration led to a significant improvement in the performance of the device.

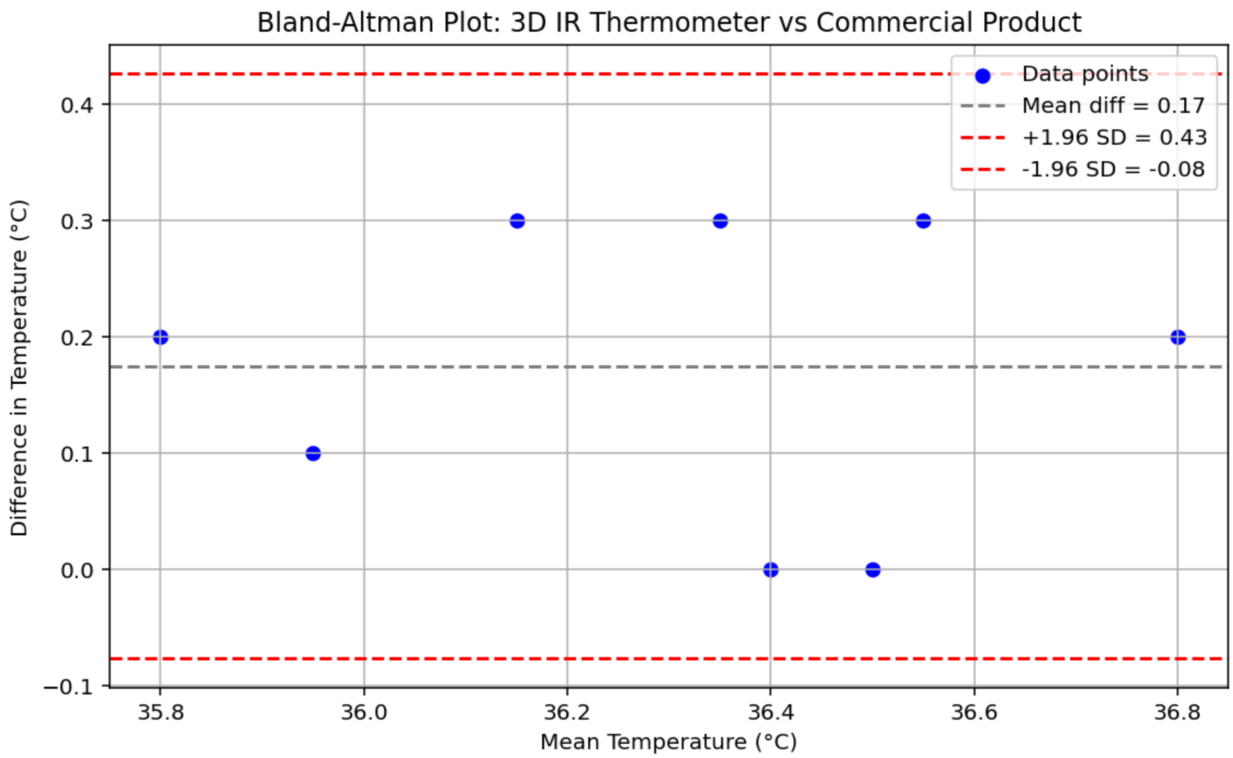

Fig 7: Temperature measurements of the Developed Infrared Thermometer after calibration

Furthermore, a standard deviation of ± 1.96 was obtained with upper limit of **Upper Limit** = +0.43°C and lower limit of -0.08 °C. The experiment revealed that the performance of the 3D printed smart infrared thermometer is reliable. The thermometer showed more consistent readings at closer proximities, suggesting that this distance could be optimal for reliable use, aligning with the typical use of hand-held infrared thermometers. The IR thermometer is suitable for use in testing body temperature, with optimal accuracy at closer ranges. Most differences cluster around 0.2 - 0.3°C, and none of the readings fall outside the agreement limits.

4.0 CONCLUSION

In this study, a 3D printed smart infrared thermometer was successfully developed and evaluated. The device can accurately measure the surface temperature of an object and transmit results remotely through instant SMS and email feedback to a mobile phone. The IR thermometer showed relative accuracy when compared with a standard commercial thermometer, with improvement in accuracy after calibration of the device. Although the wireless implementation of feedback using GSM is functional, future work may consider exploring the use of Bluetooth Low Energy (BLE) and app-based interfaces to enhance data transmission efficiency and power consumption.

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AUTHORS' CONTRIBUTIONS STATEMENT

S.C. Nwaneri: Conceptualization**,** writing – review & editing, Writing – original draft, Research Supervision, Methodology, Investigation, Formal analysis.
E.O. Mohammed: Investigations, Methodology, Software, Validation, Resources, and Writing
H.S.A. Olasore: Research Supervision, review, and editing.
All authors read and approved the final manuscript.

DATA AVAILABILITY

Datasets generated or analyzed during the current study will be made available on request.

STATEMENTS AND DECLARATIONS

ETHICAL

The current study received ethical approval from the College of Medicine, University of Lagos Health Research Ethics Committee (CMULHREC) with ethical approval number CMUL/HREC/08/24/1599.

COMPETING INTERESTS

The authors declare that they have no known competing financial or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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