A Low-Cost Online Monitoring System for Medical Refrigerator with Data Logging Functionality

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Abstract

This paper introduces a low cost and real-time temperature sensor for monitoring temperature and alerting users in case of any deviation beyond predefined threshold values automatically. This device systematically integrates an accurate temperature sensor, a Wi-Fi-enabled microcontroller and a backup battery, to send measured temperature to a NETPIE server via MQTT communication protocol for users to remotely monitor the temperature as well as for data logging. Additionally, the device is programmed to notify users via Line instant message once the temperature exceeds the threshold limits. From functionality testing on the hardware and software system, it was found that the system was able to make precise temperature reading, and all accessory systems were working as intended. As for the evaluation of the accuracy, the prototype and Fluke 289 showed their Pearson correlation of 0.999 (p < 0.001). The Bland-Altman analysis also verified the good agreement between the prototype and Fluke 289. Therefore, the prototype can be an economical alternative for providing continuous monitoring of medical refrigerator's temperature.

Keywords: *Internet of Things, Medical Refrigerator, NETPIE, NodeMCU, Temperature Monitoring*

1. Introduction

Biomedical refrigerators are used to store biological samples such as blood, blood derivatives, biological reagents, vaccines, and deoxyribonucleic acid (DNA). However, manual monitoring of refrigerator temperatures is time-consuming and requires constant attentiveness. A more efficient approach is to use a remote temperature sensor to monitor the temperatures of the biomedical refrigerators.

Biomedical refrigerators are extensively used in hospitals, blood banks, healthcare institutions, pharmacies, and in research laboratories to preserve the efficacy of the biological and chemical products stored within refrigerators (Biomedical Refrigerators, 2023). Temperature is the key parameter that controls the quality of a biomedical sample. According to the Centers for Disease Control and Prevention (2021), a temperature between 2-8 degrees Celsius is considered to be optimal for the storage of blood samples and blood derivatives. The temperature of these devices needs to be consistently monitored and controlled to maintain optimal storage temperature to ensure the quality and best possible service life of the biological samples and other temperature-sensitive products Hence, it is necessary to monitor and maintain the temperature inside biomedical refrigerators. Therefore, this paper introduces a prototype of a remote temperature monitoring device for biomedical refrigerators. The proposed device consists of a remote temperature measuring device with an on-board display interface and a backup battery. The device is meant to be positioned outside on the side of the refrigerator with its temperature sensor inserted inside the refrigerator. The temperature measurement is programmed to periodically upload to NETPIE, a cloud-based Internet of Thing (IoT) platform for remote monitoring, data logging using Message Queuing Telemetry Transport (MQTT) protocol for communication between the device and NETPIE server. MQTT protocol is a lightweight publish-subscribe messaging protocol designed for easy integration into existing applications to create internet-connected embedded systems for use in constrained environments such as low-power devices and unreliable or limited bandwidth networks, which is especially useful for Internet of Things (IoT) applications where devices need to send and receive data in a reliable and efficient manner. (Bernstein et al., 2021). NETPIE also includes a web-based dashboard which is configured to provide real-time graphical temperature and data logging functionality which can be accessed using a desktop computer or a mobile device. Moreover, the device is configured to automatically send an alert to Line, a third-party

[365]

mobile application when the internal temperature of the refrigerator exceeds or falls below a user defined thresholds after a preset duration.

In this paper, the prototype of a low-cost remote-temperature monitoring device is designed and illustrated in Section 2. Its circuit design, programming, integrated system and function are briefly described. Section 3 presents its test results including accuracy, alert condition and battery life. The discussion and conclusion are given in Section 4.

2. Objectives

In terms of the implementation of the concept in IoT for temperature monitoring device, the objectives of this study are listed as follows:

1) To develop a prototype of a low-cost temperature sensor that can be mounted on the outside of the biomedical refrigerator to monitor its internal temperature, transmit the measured data to a remote IoT server for data logging and visualization, and send a text message to alert the user if the temperature exceeds the configurable threshold

2) To perform a feasibility study to assess the performance and functionality of the prototype based on experimental results and evaluate its performance as a monitoring tool

3) To give practical and economical example of temperature monitoring device for those who have limited budget, but are in need to have such device

3. Research Methodology

The structural overview of the online monitoring system for medical refrigerator is shown in the block diagram in Figure 1. There are two main parts including hardware and online service such that the hardware is programmed to communicate with online service via internet. On hardware side, there are five axillary components including power supply, temperature sensor, control switches, output devices and related Wi-Fi component connected with NodeMCU. In online service, there are two components including Line instant messaging application and NETPIE cloud server. In reference to the integration of Internet of Thing (IoT), users can monitor and receive notification whenever the temperature exceeds the threshold limits remotely.
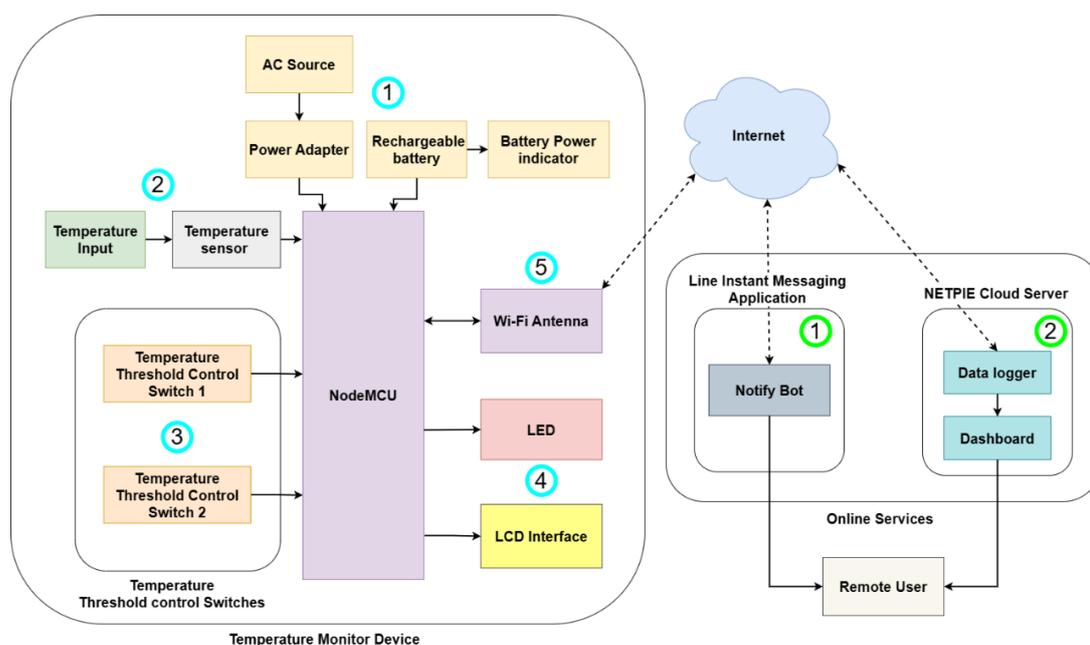

Figure 1 Block diagram of the integrated system

[366]

Regarding the implementation of the online monitoring system for medical refrigerator, circuit design, programming and system integration are carried out as follows.

3.1 Circuit Design

As regards the design of the circuit for hardware, the device was planned to have backup power supply, measure temperature reading from refrigerator, have adjustable threshold control, display temperature reading and communicate to online services. Subsequently, the schematic diagram of the prototype device was designed accordingly and shown in Figure 2.

Figure 2 Remote medical refrigerator temperature monitor circuit schematic excluding the battery module

The 20x4 LCD Interface with I2C address of 0x27 had its SDA and SCL pins connected to the D1 and D2 ports of NodeMCU board respectively. The LCD was used to display the current temperature, and upper and lower temperature threshold settings in degrees Celsius respectively.

Figure 3. Top-down image of the prototype's circuit

[367]

The DS18B20 temperature sensor had its digital data pin (DQ) connected to D7 port of the microcontroller, with a 4.7k ohm resistor connecting the sensor's data line to its VDD line. The two active-high temperature threshold control switches were connected to D5 and D8. The LED was connected to D6 using a 220-ohm resistor for indicating Wi-Fi connection status and for providing a visual indicator when the measured temperature went out of the threshold range. The device was powered by a 5V 2A DC wall charger, and by a 5000 mAh rechargeable battery, as a backup power source, which was connected to the micro-USB port of the microcontroller via a cable as a backup battery. The circuit was completed according to the schematic given in Figure 2, and the completed prototype of hardware is shown in Figure 3.

3.2 Programming and System Integration

The programming language used for this project was C++, and its source code was developed by using Arduino IDE and importing the Adafruit library files required for setting up the LCD and the other components in the system. The main program consisted of five main parts including Wi-Fi connection, MQTT server communication, alert function from Line application, the actual temperature measurement and threshold settings.

The main code was written to measure temperature once every second and to display the current temperature on the LCD. According to the creation of the working principle of device, the variables and software algorithm are given in Table 1 and 2 as follows.

Table 1 Variables used in software algorithm

Variables	Descriptions
Temp	Temperature measured by the sensor
THU = 0.0	Upper threshold
THL = 0.0	Lower threshold
Count = 0	Count up timer
LED = 0	LED status (0 = off, 1 = on)

Table 2 Overview of software algorithm

Pseudocode of the algorithm
Step 1: Connect to preset Wi-Fi network and NETPIE server.
Step 2: Recheck whether the device is connected to a Wi-Fi net and the NETPIE server.
If not, initiate automatic reconnection attempt.
Step 3: Read and display Temp.
Step 4: Check whether THU or THL switch is pressed
For i=1: 21
THU = THU+ 0.5*i;
THL = THL+ 0.5*i;
If THU = 10.5, then reset THU = 0.0
If THL = 10.5, then reset THL = 0.0
Step 5: Display THU and THL on LCD
Step 6: Compare Temp with THU and THL
If Temp >= THU or Temp <= THL, then Count = Count + 1;
Else Count = 0;
Step 7: Check whether Count exceed 20 min
If Count > 20, then set LED = 1 and notify in Line application
Else Go to Step 5
Step 8: Forward the profiles of Temp, THU, THL, Count and LED to NETPIE server

[368]

Users would be able to set the threshold temperature using tactile switches in the predefined range between 0 to 10°C. If the measured temperature went out of the threshold range for more than 20 minutes, the device would send a text message to Line application to alert the user, and the LED on the device would be powered on until the temperature reading converges to the threshold range, serving as visual alarm. With the adaptation of the codes from online sources, the Wi-Fi connection was hard coded into the microcontroller, and the temperature measurement and threshold settings are sent to the NETPIE server for storage and display on the cloud dashboard (ArduinoAll Tutor, n.d.; Maker Tutor, 2017; Name's Aomsin, 2022; Pieter, 2017). Furthermore, the device was coded to automatically reconnect to the pre-set Wi-Fi network and NETPIE server when the connections are lost, and the data log on NETPIE server was coded to store temperature readings for 30 days (Name's Aomsin, 2022). On NETPIE server, the dashboard was created to show the live feed of all variables using available widgets as shown in Figure 4. The profiles of lower limit, upper limit and live temperature readings are represented by yellow, blue and red lines respectively.
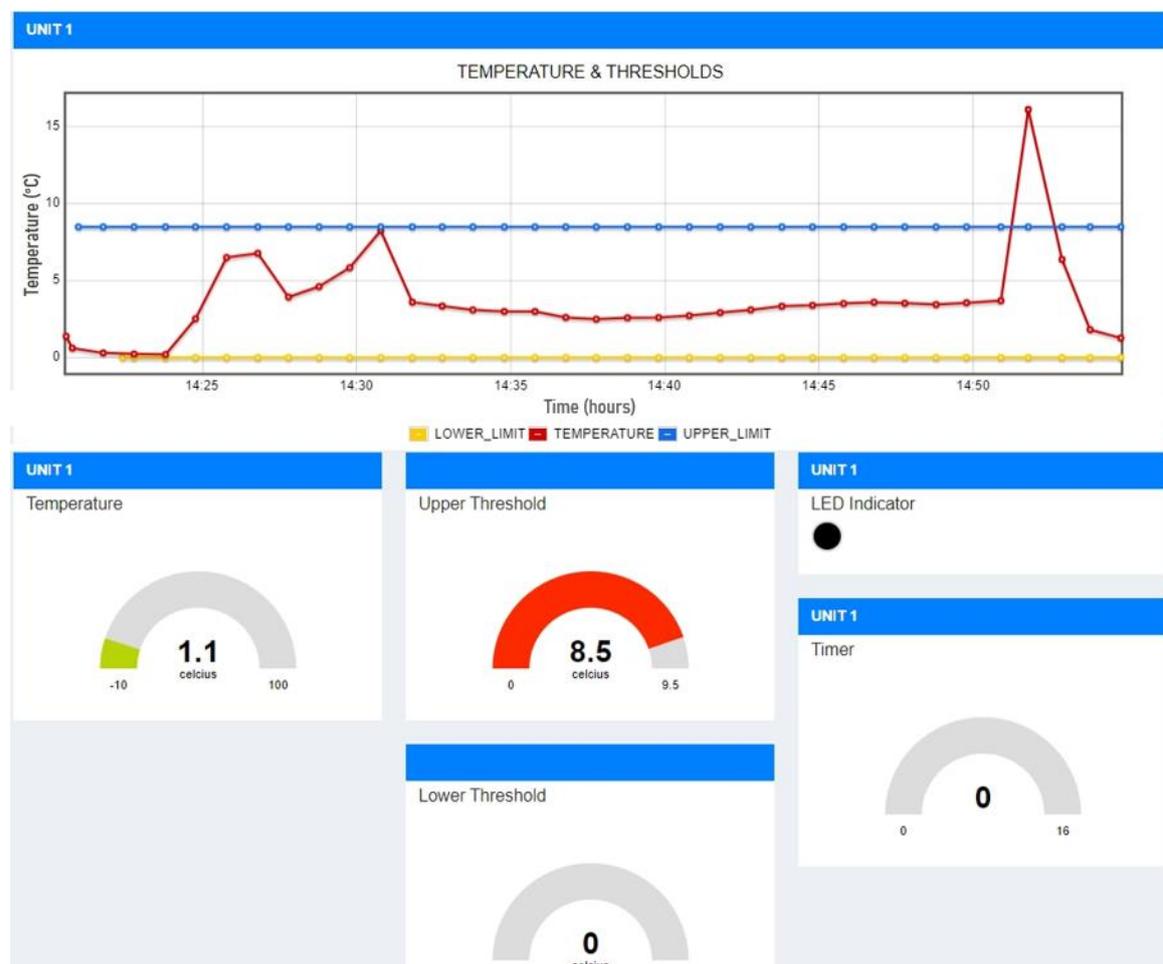

Figure 4 Dashboard created using available widgets on NETPIE server.

4. Empirical Results

After the device, software and settings on NETPIE server had been developed, its functionalities and accuracy were examined. The empirical results including functionality testing, accuracy and battery performance are according illustrated in the following sections.

[369]

4.1 Functionality Testing

In the simulated environment, the device's senser was placed inside a thermoflask containing ice. The prototype was tested successfully and found to be fully functional and operated within the acceptable criteria as defined in design consideration. The device was able to make temperature accurate measurements, displaying readings and settings on the LCD screen, as well as forward the reading to be graphically displayed and stored on the NETPIE dashboard and server respectively. The temperature threshold limiters were also employed successfully, and notification messages were sent whenever the temperature went above or fell below the threshold limits. As shown in Figure 5(a), the live feeds of temperature reading and threshold settings within and over the thresholds 2 - 8°C are displayed. For keeping the sensor inside the thermoflask, the temperature reading was sequentially compact within the threshold limits as shown in Figure 5(a). In subsequent trial, the threshold range was changed to 0 - 8°C via push buttons to test their ability to change the threshold settings. After the sensor from the flask was removed, the temperature rose beyond the upper limit as shown in Figure 5(b).
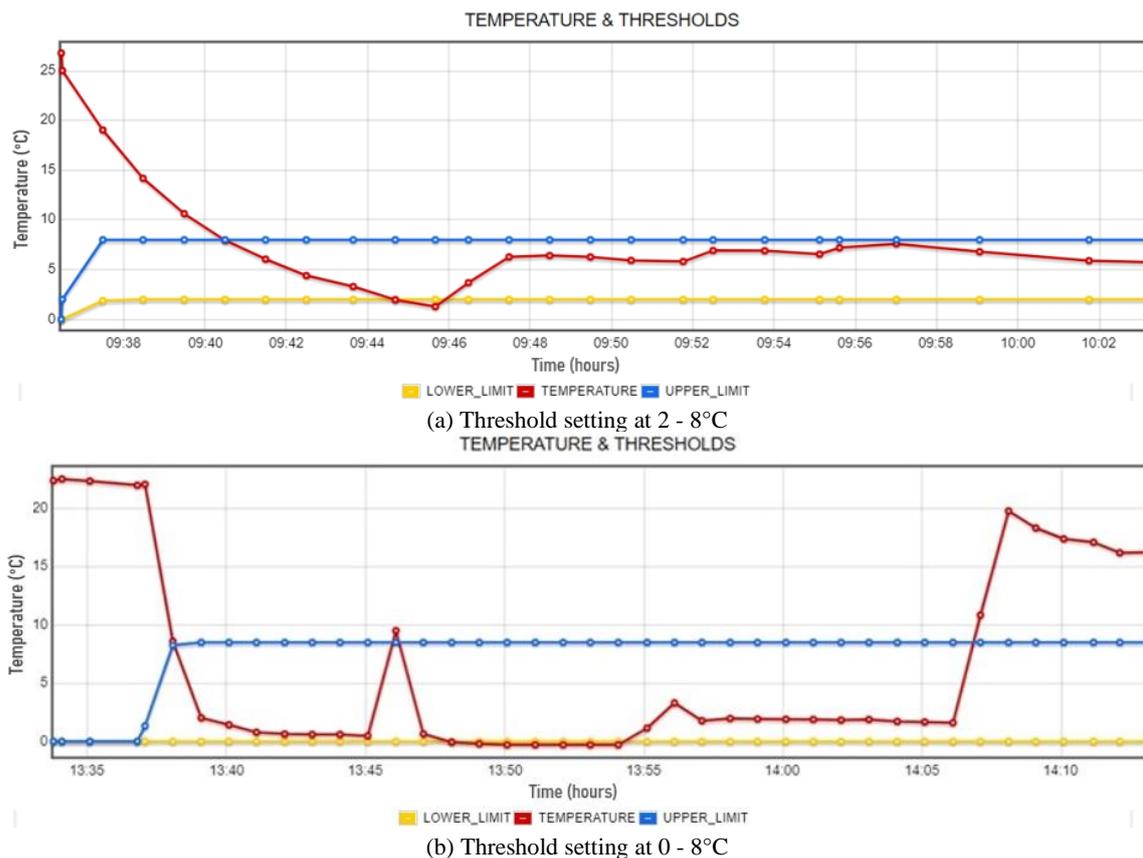

(a) Threshold setting at 2 - 8°C

(b) Threshold setting at 0 - 8°C

Figure 5 The plots of live temperature with two different threshold settings from the NETPIE dashboard

4.2 Accuracy Testing

The accuracy of the device was assessed by comparing the temperature measurements of the prototype against readings from an industrial Digital Multimeter (DMM) with thermocouple probe, Fluke 289, under low temperature from 8 to 2 degree Celsius to simulate the device's working condition inside the medical refrigerator. The temperature sensors of both devices were suspended inside the refrigerated compartment of a commercial refrigerator, Haier HR-CEQ15X, at the same position while the readings were being monitored. The refrigerator temperature was manually adjusted through the temperature

[370]

adjustment knob inside the refrigerator using temperature reading from Fluke 289 as the reference. The measurements were taken 10 minutes after each adjustment to allow temperature stabilization. When the temperatures from Fluke 289 and the developed prototype were recorded for 52 times, their correlation and agreement were statistically analyzed. Visualizing the accuracy, Figure 6(a) presents the linear relationship using scatterplot. At the significance level $\alpha = 0.05$, the Pearson correlation R = 0.999 (p < 0.001) indicates the high accuracy of prototype, i.e., the prototype and Fluke 289 directly variate and tend to show very closed number of temperatures measured each time. As high correlation does not necessarily imply that there is good agreement between Fluke 289 and prototype, Figure 6(b) shows the Bland-Altman plot to confirm their agreement. It is found that their mean differences were contained within 95% limits of agreement. Consequently, it can be seen that both Fluke 289 and the developed prototype have the very high agreement. Therefore, it is sufficient to claim that the developed prototype performance is comparable to Fluke 289.
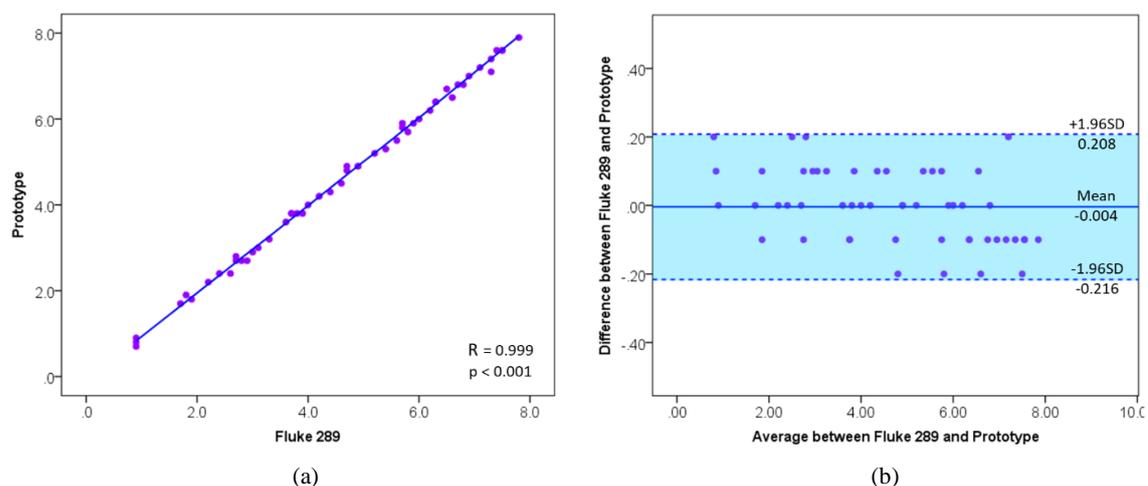

(a)   (b)

Figure 6 Linear relationship and Bland-Altman plot for Fluke 289 and prototype ($N = 52$)

4.3 Power Consumption and Battery Testing

Using a laboratory power supply, MCP M10-SP3003LX, power consumption of the decide was calculated to be 0.35 W and 0.40 W under normal load (when the temperature was within the thresholds) and under high load (when the temperature went out of the threshold range) respectively. Moreover, the 5000mAh battery used in the prototype was also tested for the maximum duration that it could power the prototype continuously on a full charge. From our experiment, the battery was able to last for maximum of approximately 14 hours after the power was cut under room temperature environment in a single charge.

5. Discussion and Conclusion

The test scenario of the low-cost online monitoring system for medical refrigerator with data logging functionality had been successfully accomplished and examined. Then, the numerical results were recorded, analyzed and interpreted. In this section, the discussion and conclusion are stated as follows.

5.1 Discussion

NodeMCU was chosen for this project due to its cost-effectiveness whereby it offers sufficient processing power and memory to implement the various components in the system. For the temperature sensor, DS18B20, a single wire digital temperature sensor capable of measuring temperatures in the range -55 to +125 degrees Celsius, was chosen for its precision and reliability at lower temperatures, necessitated by working condition inside a medical refrigerator. The system was coded to allow the users to set their temperature threshold preferences between 0 to 10 degrees Celsius instead of fixed thresholds in case where

[371]

the users may require specific threshold settings for their medical or laboratory needs. Furthermore, we have experimented with a few other IoT platforms that offers data logging and streaming functionalities similar to NETPIE; however, we found that they were not ideal for our project. i.e., limited data logging, data visualization, UI flexibility etc. Therefore, we decided to develop our system on NETPIE, which run on MQTT protocol, as it provided all the necessary features and functionalities required for the project. The information that is sent to and stored on NETPIE can be accessed by those that have the NETPIE login credential to an account which is linked to the monitoring device(s). Moreover, the system is programmed to measure and display temperature reading on the device's display interface and on the NETPIE server with precision up to 0.1 degree Celsius. Moreover, Line instant messenger was used for sending notification messages to users since the application is the most well-known and common communication software among mobile users in Thailand (The Nation Thailand, 2021).

Based on the test results, the prototype was able to perform under the testing parameters. However, the main limitation of the device is associated with the inability to selecting Wi-Fi connection preference as the device was hardcoded to connect to a preset network. However, implementation of WiFiManager library or similar library which allows user to select network preference could be implemented to increase flexibility of the device in future iteration. There are various refrigerator monitoring devices and systems currently available on the market. For instances, the TandD TR71A and Fridge-tag 2 L. These devices serve a similar purpose which is to monitor and log refrigerator temperature, with some having additional function of alarm. While these devices have smaller dimension and subsequently takes up less space and has more functionalities, our device costs less than 1,000 baht or around 31 USD to produce, shares similar features of the commercial devices for monitoring, logging temperature and alerting user to take appropriate actions, and can be constructed using basic electronic and programming knowledge. Further expansion of the project is feasible; the system can be scaled up for use system wide inside hospital or integrates the device with medical refrigerator to directly monitor and control refrigerator temperature via PID control of the refrigerator's compressor.

5.2 Conclusion

Medical refrigerators are essential instruments in healthcare facilities for storage of temperature-sensitive pharmaceuticals and samples. For preventing spoilage of pharmaceuticals or contamination of samples, most hospitals utilize medical refrigerators to safely storage temperature sensitive items for an extended period. However, the common practice of manual monitoring of the temperature is time-consuming and prone to human errors. This paper presents a low-cost remote monitoring device for biomedical refrigerators. The objective of this project was to economically develop the necessary hardware and software for measuring temperature inside the refrigerator with adjustable temperature threshold limits. Whenever the temperature fell outside of user-defined limits, the line application will alert the users and the LED as visual indicator will be powered on, simultaneously. Additionally, the temperature reading and temperature threshold settings were sent a cloud server for storage and for remote viewing. All of the objectives were met. Overall, the device prototype performed well and was able to measure temperature accurately, upper and lower temperature limits could be set and was functional, and the device could communicate with the cloud servers and store data reliably. This design offers an economical and functional alternative for temperature monitoring of medical refrigerators for community and veterinary clinics, or those who are in need of such device. For the further application, this device could be expanded to food industry to provide constant monitoring the temperature of frozen food (seafood and meat), ice-cream, dessert, ready-to-eat meals, frozen fruits and vegetables.

6. Acknowledgements

[372]

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