Sensors and Materials, Vol. 35, No. 5 (2023) 1731–1740
MYU Tokyo

S & M 3283

Using Edge Computing Technology in Programmable Logic Controller to Realize the Intelligent System of Industrial Safety and Fire Protection

Liguo Su,[1,2] Yang-Han Lee,[3*] Yi-Lun Chen,[2]
Hsien-Wei Tseng,[4] and Cheng-Fu Yang[5,6**]

[1]Minxi Vocational and Technical College, Longyan, Fujian 364000, China
[2]Universiti Kuala Lumpur Malaysian Institute of Information Technology, Kuala Lumpur 50250, Malaysia
[3]Department of Electronic and Computer Engineering, Tamkang University, New Taipei City 251, Taiwan
[4]College of Artificial Intelligence, Yango University, Fuzhou, Fujian 350015, China
[5]Department of Chemical and Materials Engineering, National University of Kaohsiung, Kaohsiung 811, Taiwan
[6]Department of Aeronautical Engineering, Chaoyang University of Technology, Taichung 413, Taiwan

(Received January 7, 2023; accepted April 25, 2023)

Keywords: factory safety, Bluetooth sensor, edge computer, intelligent judgment, programmable logic controller (PLC)

One reason behind a factory fire is personnel neglecting to pay attention to various details within the factory. For instance, environmental temperature can impact the safety of storage facilities, whereas humidity levels can affect the frequency of electrostatic discharge incidents. However, it is not feasible for workers to continuously monitor the changes in the factory environment and inspect equipment. Therefore, we investigated a method that can help provide intelligent judgments and can assist workers in monitoring the factory environment by using Bluetooth sensors and edge computers. The intelligent fire protection system designed in this study is characterized by the wireless transmission and easy arrangement of Bluetooth sensors, and is equipped with an edge computer on the production line. This system can make intelligent judgment on the environment and send a message to notify the users when the environment changes very rapidly. If the data captured from the environment exceeds a critical threshold requiring a warning, an alarm will notify the users. If required, the edge computer will take control of the programmable logic controller of the production line to implement relevant actions and achieve an intelligent automatic fire protection system.

1. Introduction

In the past, many methods were developed as fire alarm systems.(1–6) For example, Ku and Kim proposed an autonomous fire-alarm-system-based home network system and the communication technology of Internet of Things (IoT), which could provide a real-time fire alarm after smoke is detected in a resource-constrained environment.(1) Imteaj *et al.* designed a fire alarm system using an Arduino Mega system and Raspberry Pi 3B+.(2) The Arduino system

*Corresponding author: e-mail: yhlee@ee.tku.edu.tw
**Corresponding author: e-mail: cfyang@nuk.edu.tw
https://doi.org/10.18494/SAM4323

can use chemical and multiple optical sensors to sense smoke and flames, which can be used to determine abnormalities in the environment. The Arduino system can also be used with an automatically controlled lens module to observe abnormal positions, and the detected signals can be transmitted via ESP-01 using the Wi-Fi system to connect the Arduino IP to a router. The Raspberry Pi 3B+ will also use Python language to access each Arduino IP through the router. If the sensors in the Arduino system have detected an abnormal environment, the Raspberry Pi 3B+ will transmit the alarm address and image to the relevant fire department through a GSM module.(2–5)

Traditional fire sensors typically rely on a single sensing method, such as optical or thermal detection;(7–10) in contrast, Bluetooth sensors use various sensing modules to continuously obtain various environmental data. Bluetooth modules are different from traditional fire sensors when a fire is detected. Traditional fire sensors transmit the fire alarm to a fire control switchboard using physical wires, whereas the Bluetooth sensors used in this study utilize Bluetooth signals for transmission, providing the device with characteristics such as easy installation and the ability to be multiplexed. The edge computer differs from traditional fire-received switchboards in that it is connected to sensors via wires, and it is capable of scanning through built-in Bluetooth devices to collect Bluetooth signals, including environmental data, sent by the sensors. The edge computer can then perform data calculations and make judgments on the basis of this data. The edge computer can take relevant actions based on the results of its analysis, such as reminding users when environmental conditions change very rapidly and require special attention. In this way, the users can be reminded to take preventive actions, and the camera modules can be used to transmit real-time images to remote users.

The primary objective of this study is to design an intelligent fire protection system that combines the Pi Camera V2 lens module and Raspberry Pi 3B+ to create an edge computer.(7,8) The detection method of this system is mainly through Bluetooth sensors because Bluetooth sensor devices have the characteristics of wireless transmission and easy arrangement. To make intelligent judgments on the environment, the sensors are also equipped with edge computers on the production line to achieve functional enhancement. The edge computer can collect and scan Bluetooth signals, perform data calculations, and make judgments on the basis of collected information. The collected signals contain the environmental data and can be sent by the Bluetooth sensors through the built-in Bluetooth devices. If the environment changes very rapidly, a notification message is sent to alert users to pay attention to the conditions. Additionally, if the environment data exceeds the warning threshold, an alarm is triggered to further alert users. If necessary, the edge computer will take proactive measures to control the programmable logic controller (PLC) of the production line and initiate relevant actions to drive the intelligent automatic fire protection system, so as to realize an intelligent automatic fire protection system.

2. Research Methods and Steps

The fire protection system investigated in this study is divided into three parts. Bluetooth sensors are responsible for the collection of environmental data, an edge computer is responsible for data analyses, and a programmable logic controller (PLC) is responsible for handling the production lines when abnormal conditions happen. The system is also integrated with Line Notify to provide users with reward functionality. The Bluetooth sensors are responsible for the collection of environmental data and transmitting it to the edge computer through the Bluetooth broadcast system. Upon receiving the data, the edge computer stores and analyzes it. If the data is determined to be abnormal, the edge computer sends a notification to users and uses Line Notify to control the PLC for any necessary processing.

This system uses the timer on Arduino UNO, where the data of the thermometer, smoke sensor, and flame sensor are read every 200, 300, and 650 ms, respectively. The Bluetooth module updates data every 700 ms, and a watchdog is initiated every 20 s to confirm the device status. The Bluetooth broadcast will continuously transmit sensing data, and the broadcast will only stop when the Bluetooth data is updated. Arduino UNO is developed by Arduino Co., Ltd. This circuit uses the open source control board of the Microchip ATmega328P microcontroller. This development board can use the built-in Type B USB interface to connect with a computer, and it can utilize the open-source software Arduino IDE to write programs, which enables rapid hardware and software development.

The Aosong DHT-22 digital humidity and temperature sensors in the system, which were calibrated by the manufacturer, use digital signals as output digital signals. The sensor consists of a capacitive humidity sensing element and an NTC temperature measuring element. The DHT-22 is connected to a high-performance 8-bit single-chip microcontroller, and its calibration data is stored in OTP memory in a program form. As a result, the sensor offers several advantages such as low power consumption, compact size, ease of development, and fast response time; the parameters are shown in Table 1. In this study, the SHARP GP2Y1014AU with optical detection method was used to detect air particles. The internal design of the sensor, which is equipped with photoelectric crystals and diagonal infrared diodes, allows for the measurement of tiny particles with sizes larger than 0.8 μm. These particles are detected using the reflected light of suspended particles in the air. The sensor has the advantages of small size and low power consumption, and its parameters are outlined in Table 2.

In this study, the KY-23 device, which is applicable to various types of flame, is used to sense flames. The principle is to use the flame's strong infrared characteristics, and an infrared receiving tube is used to sense the flame. Then, the sensed flame infrared intensity is converted into electrical signals with high and low changes; the parameters of the KY-23 device are shown in Table 3. The JDY-18 module, which is used as the communication module, operates on Bluetooth 4.2 protocol and is also compatible with Bluetooth 5.0. Its frequency band is 2.4 GHz,

Table 1
Parameters of DHT-22 device.

Working voltage	3–5.5 V
Temperature measurement range	−40–80 °C
Humidity measurement accuracy	2% RH
Humidity measurement range	0–100% RH
Temperature measurement accuracy	0.5 °C
Signal type	Digital signal

Table 2
Parameters of SHARP GP2Y1014AU device.

Working voltage	5 V
Current consumption	11 mA
Output voltage (no dust)	0.9 V (typical)
Signal type	Digital signal
Sensitivity	0.5 V/(0.1 mg/m^3)

Table 3
Parameters of KY-23 device.

Working voltage	3.3–5 V
Detection angle	60 °C
Detectable light wavelength	760–1100 nm
Signal type	Digital and TTL outputs

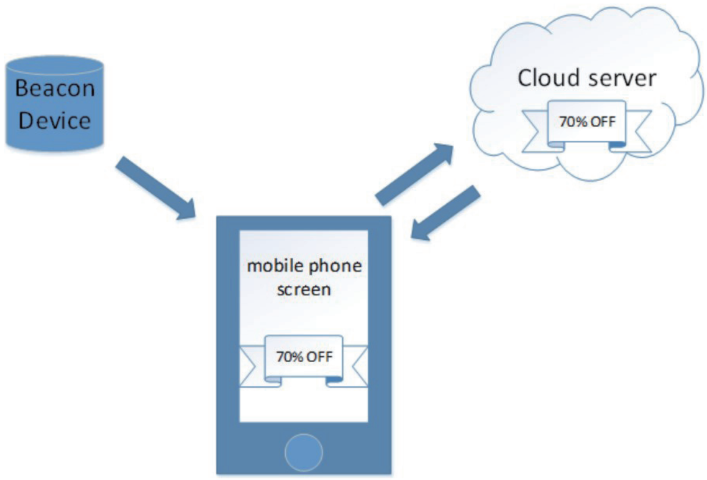

Fig. 1. (Color online) Schematic diagram of beacon.

and users can customize settings such as device name, transmission power, working mode, and pairing password using AT commands. The device supports various working modes, including the probe mode, iBeacon broadcasting, and master–slave pairing.

Bluetooth Beacon, which is built on the Bluetooth Low Energy protocol, is a broadcast technology suitable for devices that already have Bluetooth low-energy communication capabilities. When using Bluetooth low energy technology, it sends its unique data packet to surrounding devices, in which the data packet is very short and contains the Service Universally Unique Identifier, short data, and Received Signal Strength Indication. The beacon broadcasts its data packet to the surrounding devices at regular intervals, and the data packet can be received by any supported Bluetooth device. This technology is often used for product promotion using a mobile app or for accurate indoor positioning, as shown in Fig. 1.

3. Results and Discussion

In this research, we combined the Pi Camera V2 lens module and the Raspberry Pi 3B+ as the edge computer; the structure of the edge computer is shown in Fig. 2. Three important tools are used to achieve this purpose, namely, Bluepy, SQLite, and Line Notify. As shown in Fig. 2, the Raspberry Pi 3B+ is a Linux-based single-board computer; it has an ARM Cortex-A53 processor, an Ethernet interface, Bluetooth 4.2BLE, WiFi, and 1 GB of memory. The Pi Camera V2 lens module has 8 megapixels and uses the CSI interface to connect to the Raspberry Pi. In

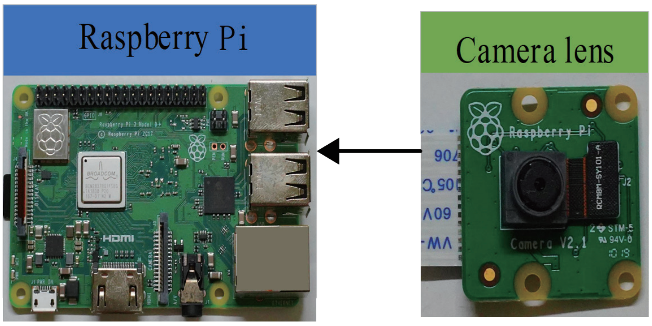

Fig. 2. (Color online) Structure of edge computer.

this study, it is mainly used for capturing fire images to report back to users. The workflow of the edge computer can be divided into three parts: scanning and collecting data from the Bluetooth sensor, performing algorithms on the collected data to determine if the environmental conditions are abnormal, and finally, sending notifications and controlling the PLC if necessary. The third is to notify the users or control the related equipment when the data judgment result is abnormal.

Apple's iBeacon, which uses Beacon technology, was introduced to the market in 2013. The iBeacon packet includes UUID and RSSI, as well as other formats. The short data are divided into Minor and Major, each with 16 bits. In this study, Minor and Major are used to transfer sensor data. To ensure a smooth transmission of data regarding fire, smoke, humidity, and temperature through the iBeacon protocol, it is important that the raw data from each sensor module is not very large. This will enable the data to fit entirely into the Minor and Major fields. Therefore, to convert the data of each sensor, the approach shown in Fig. 3 is used. Both the temperature and humidity data obtained from the sensors are floating point numbers using 32 bits. Given the sensor's accuracy to one decimal place and range from 0 to 100, the data is multiplied by ten and converted into the integer format, resulting in a 10-bit data size. After the humidity and temperature data each occupy 10 bits for the Minor and Major fields, there are still six bits left available for both the smoke sensor and the fire sensor. The values detected by the smoke sensor range from 0 to 3000 and occupy 12 bits. In this study, they are mapped proportionally to the range of 0 to 63, which will take up the remaining six bits of the Major field. The flame sensor produces integer values ranging from 0 to 1023 (10 bits), which are proportionally mapped to a range of 0 to 63 in this study. These mapped values take up the remaining six bits of the Minor field.

There are two ways to judge the abnormal data, as shown in Fig. 4. The first step is to use statistical analysis to determine the normal distribution of the latest 100 Bluetooth sensor data. If any scanned Bluetooth sensor data exceeds this normal distribution, it is considered an indication that the environment has changed very rapidly. To calculate the normal distribution, two formulas are used: Eq. (1) to calculate the mean and Eq. (2) to calculate the standard deviation.

$$avg = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{1}$$

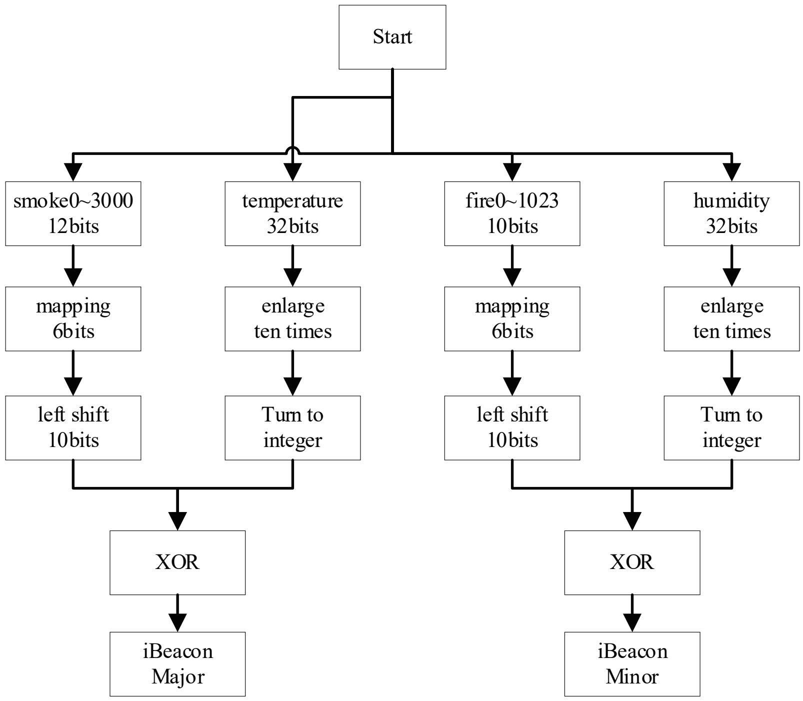

Fig. 3. iBeacon data flow chart.

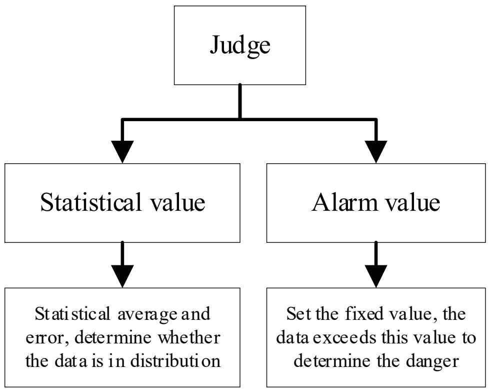

Fig. 4. Flow chart of data judgment.

$$std = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - avg\right)^2} \tag{2}$$

To determine the standard deviation, we can use statistical analysis and calculate the normal distribution of the 100 most recent Bluetooth sensor readings. This can be performed by applying the principles of the normal distribution in statistics, as shown in Eqs. (1) and (2). If the Bluetooth sensor data deviates significantly from the normal distribution, we can infer that the environment has undergone a rapid change. A normal distribution typically includes 99.7% of data points that lie within three standard deviations from the mean.

The second approach involves establishing abnormal value boundaries based on environmental conditions. When the set value for abnormal value boundaries is exceeded, it is considered an environmental abnormality. For instance, when dealing with temperature, 33 °C is the maximum comprehensive temperature and heat index for light work according to the standard for labor and rest time for high-temperature work. However, in the experimental environment, it is set at 40 °C. Regarding humidity, during a fire, the temperature rise leads to a drop in humidity. Thus, the humidity alarm is set at lower than the normal level of 30% relative humidity (RH). In the case of fire, the sensor may be affected by indoor lighting, causing some error. To prevent misjudgment, the fire detection value is set to level 15. As for smoke, the corresponding data in the datasheet indicates that poor air quality corresponds to a value of 30.

In this experiment, the PLC is used to simulate a production line with a fire extinguishing device, and work instructions are obtained by continuously communicating with the edge computer, as shown in Fig. 5. On the basis of the simulation results, the constructed system operates as follows: when the edge computer learns that the Bluetooth sensor has detected a fire, it sends a fire extinguishing action to the PLC via the socket interface, and the PLC reports that the fire is being extinguished. The fire extinguishing action continues until the Bluetooth sensor no longer detects the fire, at which point the edge computer issues an end of fire extinguishing action signal, and the PLC reports the end of the fire extinguishing action and returns to normal operation.

To simulate the condition of abnormal temperature and humidity changes, the training and sensing effects of the Bluetooth temperature and humidity sensors need to be confirmed. To

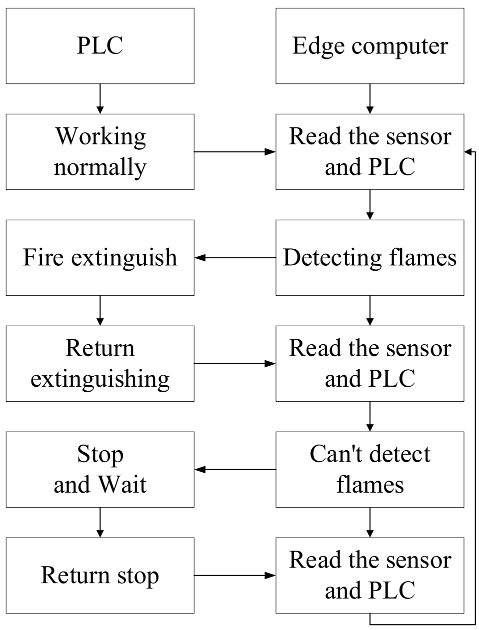

Fig. 5. Work flow chart of PLC and edge computer.

enable the edge computer to collect data and determine the normal distributions of temperature and humidity fields, the Bluetooth temperature sensor is initially positioned inside a transparent acrylic box for at least 30 min. After the edge computer acquires data on the normal distributions, a blower located in the hole of the acrylic box is activated to warm up the interior. At 1700 s, hot air from a hair dryer is sent into the constructed simulation system, and the measured results are presented in Fig. 6 as the detection results of the humidity and temperature sensors. Simulation system data indicate that, once the hair dryer begins heating (at 1700 s), the temperature surpasses the statistical normal distribution range, and the humidity drops below the previous environment's statistical normal distribution range as recorded in the edge computer. At this time, the system sends a Line Notify message to the users, and this action mainly wants to warn the users that the ambient temperature and humidity change very rapidly. If the temperature exceeds 40 ℃, the users will promptly receive a notification via Line Notify informing them that the ambient temperature has become excessively high.

To simulate the conditions of smoke and fire, the training and sensing effects of the Bluetooth smoke and fire sensors need to be confirmed. First, Bluetooth sensors are also placed in a transparent acrylic box for more than 30 min to allow the edge computer to collect data and obtain the normal distributions of the smoke and fire fields. To simulate the generation of smoke (dust shown in Fig. 7), an incense stick is lit at 530 s to simulate the generation of smoke before a fire will occur. The edge computer promptly sends a Line Notify message to notify users of the presence of smoke once it is detected. In addition, the incense stick smoke is detected by the sensor, and a candle is lit at 600 s to simulate a fire. Once the edge computer detects a fire, it

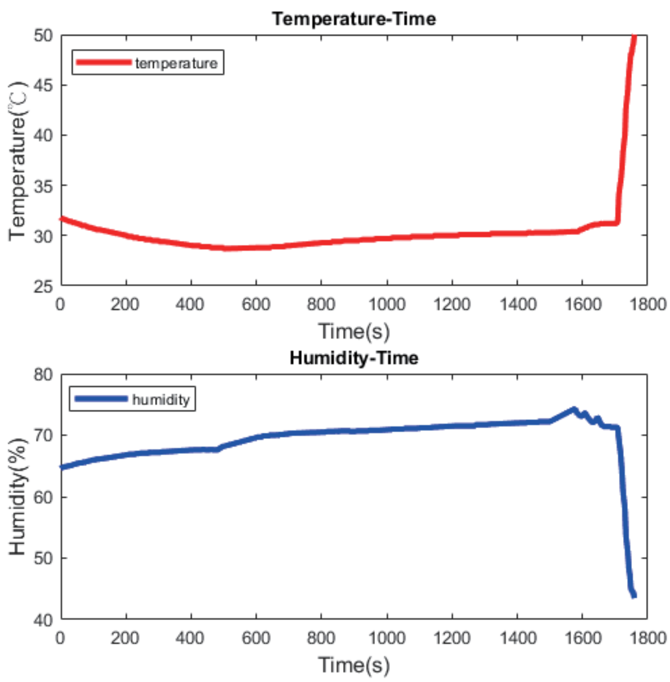

Fig. 6. (Color online) Simulation data record diagram of abnormal temperature and humidity changes.

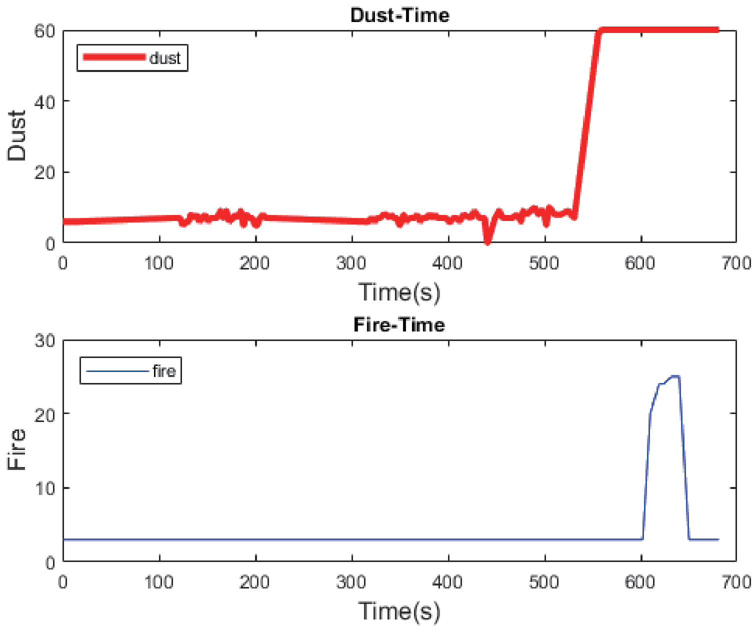

Fig. 7. (Color online) Simulation data record diagram of smoke and fire.

immediately activates the camera module to capture images of the scene and sends the scene status to users via Line Notify. Then, the fire extinguishing system will be activated, and the fire on the candle is destroyed 50 s (at 650 s) after it is discovered. The data record of the experimental process is shown in Fig. 7, which apparently presents the time to detect the smoke and fire. The results in Figs. 6 and 7 show that an intelligent system that can achieve industrial safety and fire protection can be actually realized using the designed system.

4. Conclusions

The intelligent fire protection system proposed in this paper is expected to be used on production lines as an early warning system. The edge computing technology in a PLC is successfully used to realize an intelligent industrial safety and fire protection system. The fire investigation system comprised Bluetooth sensors for environmental data collection, a PLC responsible for managing abnormal conditions on a production line, and an edge computer for data analysis. Three important tools are used to achieve this purpose, namely, Bluepy, SQLite, and Line Notify. Abnormal data are determined by two methods: the first involves the statistical analysis of the normal distribution, where the latest 100 Bluetooth sensor data points are used to calculate the normal distribution; the second involves setting abnormal value thresholds based on environmental conditions. In the constructed simulation system, the abnormal temperature and humidity changes and the occurrence of smoke and fire are actually detected. The signals for the four conditions have been successfully sent to the users through the Line Notify, and the fire on a candle is destroyed 50 s after it is discovered.

Acknowledgments

This work was supported by projects under Nos. MOST 110-2622-E-390-002 and MOST 110-2221-E-390-020.

References

1. D. Ku and H. Kim: Int. J. Adv. Comput. Electron. Eng. **6** (2019) 2394.
2 A. Imteaj, T. Rahman, M. K. Hossain, M. S. Alam, and S. A. Rahat: 2017 Int. Conf. Electrical, Computer and Communication Engineering (ECCE) (2017) 899–904.
3 T. Shwetha and S. L. Mukthi: J. Emerg. Technol. Innov. Res. **6** (2019) 283.
4 K. Sangam, T. Prasanna, and K. Bramaramba: Int. J. Eng. Technol. Res. **8** (2019) 103.
5 B. Prabha: Proc. 3rd Int. Conf. IoT in Social, Mobile, Analytics and Cloud (I-SMAC) (2019) 414–419.
6 N. G. Praveena, D. Deepa, and M. Manju: Inter. J. Sci. Technol. Res. **9** (2020) 6444.
7 M. S. Bin Bahrudin, R. A. Kassim, and N. Buniyamin: 2013 Int. Conf. Electrical, Electronics and System Engineering (ICEESE) (2013) 43–48
8 A. Imteaj, T. Rahman, M. K. Hossain, M. S. Alam, and S. A. Rahat: 2017 Int. Conf. Electrical, Computer and Communication Engineering (ECCE) (2017) 899–904.
9 R. I. Rashid, S. M. Rafid, and A. Azad: 2018 IEEE Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER) (2018) 49–54.
10 S. Sharma, K. Chand, D. Sharma, and P. Guha: 2018 Int. Conf. Sustainable Energy, Electronics, and Computing Systems (SEEMS) (2018) 1–5.