A WIRELESS DISTRIBUTED FORMALDEHYDE SENSING SYSTEM USING COST-EFFECTIVE SELF-DEVELOPED CIRCUITS AND PROGRAM

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A wireless formaldehyde sensing system has been experimentally developed and proposed. It consists of four self-developed sensor nodes, a wireless controller and graphical interface developed by using LabVIEW. Each sensor node has a formaldehyde sensor, driving circuits, a wireless module and other essential circuits. Experiments were carried out and results demonstrate that the proposed system has the ability to detect multi-points formaldehyde concentration with numerous advantages. It can be applied for monitoring in-door formaldehyde concentration for research or commercial purposes. In the future, the proposed system will be further optimized for such applications.

Keywords: formaldehyde detection, sensor node, wireless communication, distributed sensing system;

1. Introduction

Detection of hazard gases within buildings including formaldehyde, methane, carbon monoxide and ammonia etc. is crucial for public safety [1-3]. Nowadays, many architectures including residential buildings, office buildings and campus buildings have been designed with good airtightness feature for achieving high energy saving target. However, these new super-insulated buildings places the quality of indoor air at the center of the debate considering the environmental-friendly performance of building materials and furniture [4-8].

Hazard gases within buildings are dangerous in different ways including toxic, flammable and explosive. Among the hazard gases, formaldehyde (HCHO) is colorless volatile organic compound (VOC) that can even cause terrible diseases or death [9-10]. It can be slowly released by furniture made of agglomerated wood, textiles, paints and cosmetics [11-12]. Generally, its

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concentration should not higher than 60 – 80 ppb in buildings according to regulations or laws in many countries [13-15]. Formaldehyde has been classified as carcinogenic to humans by the International Agency for Research on Cancer since 2004 [16-17]. In addition, there are other hazard gases such as carbon monoxide and methane that can lead to headache or asphyxia and explosion respectively. Therefore, detection of these hazard gases has been researched world widely in recent years [18-20].

Detection methods include chromatographic, chemical and spectroscopic methods have been reported by many researchers [22-23]. It can be found out that traditional methods such as the reference method has drawbacks including expensive, inconvenient and time-consuming analyses. Spectral absorption method is able to achieve fast response, large sensing scope and real-time detection targets but systems based on spectral absorption theory are usually expensive and large size. Another drawback of these systems is that they cannot monitor formaldehyde concentration in multiple areas at the same time. Therefore, electrochemical HCHO sensor has been developed with accuracy sensing ability, compact size and low detection limit features in order to overcome the drawbacks of traditional methods [24-28].

In this paper, a distributed formaldehyde detection system has been developed. It consists of 4 sensor nodes with wireless communication feature, a wireless receiver and software developed by using LabVIEW. The hardware of sensor nodes and wireless receiver were self-developed and tested. The software can receive data, display data and store data. This system is able to detect HCHO concentration in multiple areas by using these wireless connected sensor nodes. In addition, it can perform long-term monitoring of HCHO concentration which is essential for evaluating the performance of formaldehyde removal methods. Experiments were carried out to monitor the HCHO concentration of a newly decorated laboratory and evaluate the performance of the developed system. Results demonstrate that the system is able to meet the requirement of long-term monitoring of indoor HCHO of multiple areas. In the future, more wired and wireless sensor nodes will be adopted in this system in order to achieve long-term distributed HCHO monitoring in a larger region within building.

2 System structure

The developed sensing system can be divided into four logical layers which are physical layer, support layer, system layer and application layer as shown in Fig. 1. First of all, in the physical layer, multiple wireless sensor nodes have been developed and deployed in different regions in building for multiple-points gas detection. Each sensor node consists of a HCHO sensor, a controlling sensor board, a wireless module and I/O ports. It converts HCHO concentration to electrical signal and is sending signal to sensor node controller by wireless communication. The wireless transmitting frequency is 433 MHz which has a longer communication distance than normal 2.4 GHz frequency. Secondly, a wireless sensor node controller has been developed to communicate with the multiple sensor nodes. It has a USB port which is responsible for supplying DC power and data transmission. It has two major parts which is the main controller chip STM32F103RCT6 and a wireless module. Thirdly, a computer installed with the driving files of CH340G chip of sensor node controller has been deployed to store and display data. Finally, developed GUI based on LabVIEW is the application layer. It can display detected data and also can create files on the hard disk of the computer to store the collected data.

In this system structure, there are two hardware parts and 1 software part which have been developed to meet the requirement of the system. In the following section, design details of the developed hardware and software is demonstrated.

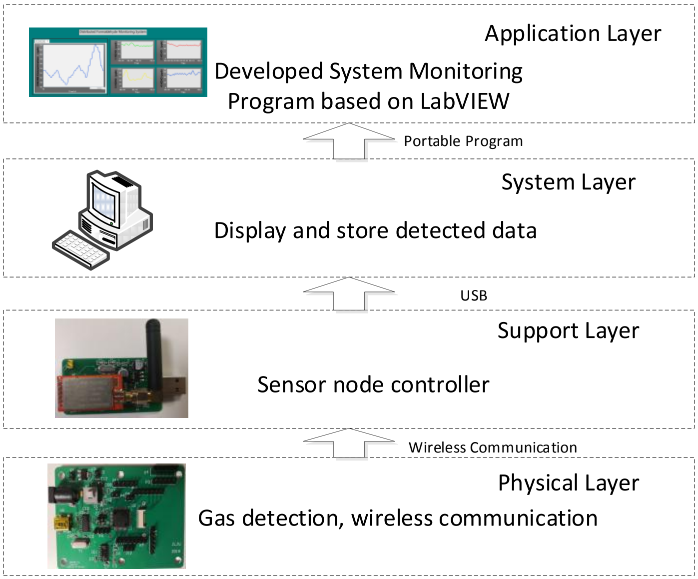


Fig. 1. System structure of the developed HCHO sensing system

3 Developed key modules

3.1 Sensor node

In the sensing system, there are multiple sensor nodes which can be applied to detect specific areas. Currently, four sensor nodes have been developed and have been tested in experiments. Each sensor node consists of a controller PCB, a HCHO sensor, a wireless module, a plastic ventilated case and supporting parts. The sensor and the wireless module are connected with the controller PCB. There is a power supply socket embedded on the side panel of the case. The photo of a sensor node is shown in Fig. 1.

The functional block diagram of a sensor node is shown in Fig. 2. The controller PCB namely sensor node board has numerous functional parts which are located in the imaginary line block in Fig. 2. It consists of several major parts including the MCU circuit, power supply circuit, sensor circuit and communication circuit. The power supply of the sensor node is 5V DC. The MCU is IAP15F2K61S2. It has 61 KB FLASH and 2 KB RAM on chip. The board has two ways to be connected with a PC. One is the wired method by using the serious circuit. In this circuit, a chip CH340 has been adopted to convert TTL voltage to USB voltage. Therefore, the sensor node can be linked with PC by using a USB cable. The other way for communication is wireless. The MCU of the sensor node can send the collected data to PC by using the 433MHz wireless module. The data can be received by a sensor node controller which is linked with PC as shown in Fig. 2.

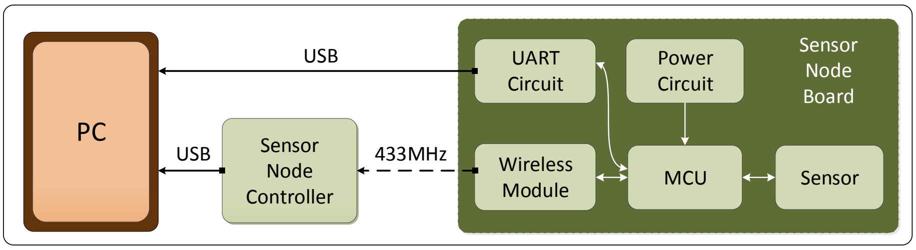
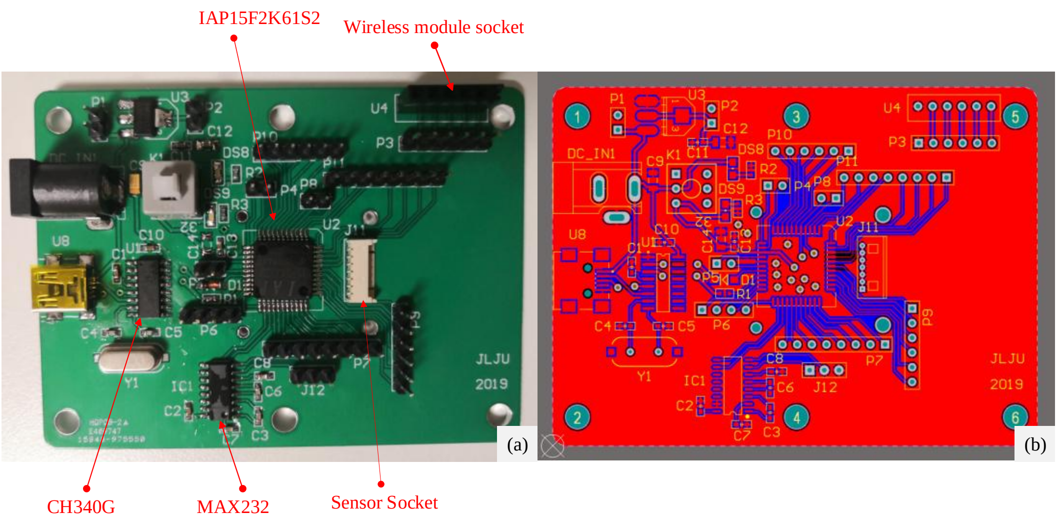


Fig. 2. Functional block diagram of the developed sensor node

The developed circuit board is shown in Fig. 3 (a). In this Fig., it can be seen that the essential components have been already soldered manually. There is a DC-005 power supply port mounted on the PCB for supplying 5 V DC power to the circuit. The macro-USB port and the CH340G circuit is for downloading program from PC to the board. There is another chip, Max232, is also integrated in this circuit board for communication between the main controller chip and PC via UART. The sensor socket with 7 pins is connected with the main controller chip for direct data transmission. The HCHO sensor’s type is ZE08-HCHO, which is a compact electrochemical sensor. It has two output methods which are DAC output and UART output. In this paper, the UART output has been applied for data communication. The response time of the sensor is less than 60 seconds and the detection scope is 0 – 5 ppm. Generally, the concentration of HCHO in ambient atmosphere is less than 100 ppb so the detection range is wide enough for indoor detection. The resolution of the sensor is less than 10 ppb and the working temperature range is -20 – 50℃. In addition, the sensors applied in this system need to be calibrated every year according to the datasheet. There are two method to calibrate the sensors without sending them to their manufactory. The first way is to compare the result and calibrate the sensors to an accurate sensing system or a new same type sensor. The second way is to compare the measurement results of multiple sensors and to calibrate them by using fitting formulas of the average value in their control programs to modulate the outputs. The wireless module can be mounted on its own socket as shown in the photo. The main controller chip, IAP15F2K61S2, has 44 pins and the idle I/O ports are also fan-out for further utilities. The two side PCB drawing is shown in Fig. 3 (b).

Fig. 3 Designed PCB (a), manufactured PCB (b) and manually soldered PCB (c) of



sensor node

3.2 Sensor node controller

The sensor node controller has been developed to send and receive data with the multiple sensor nodes via wireless communication as shown in Fig. 4. It has a USB port which is for power supply and data transmission. And there is a wireless module mounted on the developed board as shown in Fig. 4 (a). The wireless module is SI4438. It has SPI serial protocol and the working frequency is 433 MHz (425M – 525 MHz).

The PCB layout of the board is shown in Fig. 4 (b). The main controller chip of the board is STM32F103RCT6, which is a 32-bit ARM core monolithic chip. It sends data to PC while it is receiving data from the sensor nodes. Also, it can request specific data from the sensor nodes when it receives command from PC. It is a double side PCB and was soldered manually. Along with the main control chip STM32F103RCT6, the serial-USB chip CH340 is also adopted on this board. The rest components on the board are including crystal oscillators, resistors, capacitors, inductors and I/O ports. The sensor node controller sends data to computer via the serial communication protocol and a graphic interface has been developed to communicate with the sensor node controller based on LabVIEW.

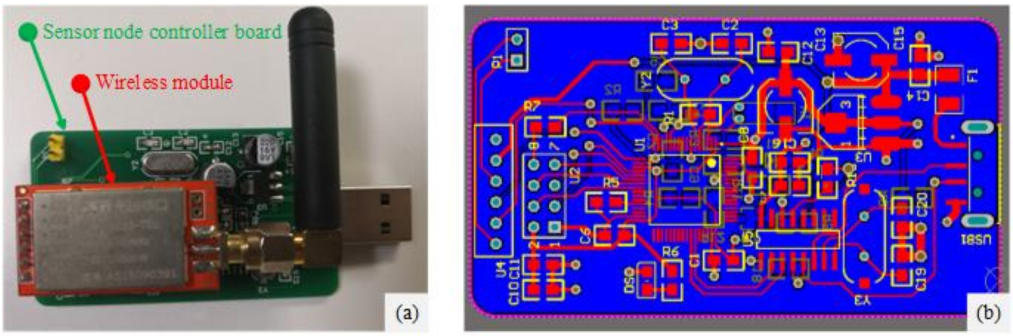


Fig. 4 Photo of the integrated sensor node controller (a) and PCB layout of the developted sensor node controller board (b)

3.3 LabVIEW GUI

The front panel of the developed LabVIEW program is shown in Fig. 5. The developed program consists of UART communication module, display sub-VI, data store sub-VI and other essential modules. In this distributed HCHO sensing system, there are four sensor nodes that can work separately. Therefore, they can be placed to different zones to monitor HCHO concentration in order to achieve flexible and accurate results. They can send the collected data to the computer via wireless communication and the LabVIEW program will display the long-term monitoring concentration data in 4 separate windows that are show on the right side in Fig. 5.

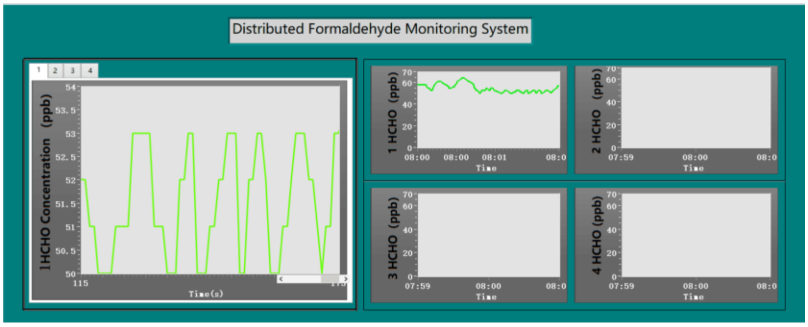


Fig. 5. Developed interface of the HCHO sensing system based on LabVIEW

The left side of the program is a bigger window for displaying short term concentration. It can be switched among the 4 channels and the scale can be adjusted as well. In Fig. 5, only one channel is working and the left window shows a small part of the detected data. In the following section, performance of the developed LabVIEW program is demonstrated with 4 channels HCHO detection.

4. Experiments

In this section, numerous experiments are demonstrated in order to evaluate the performance of the proposed HCHO sensing system. In these experiments, four developed sensor nodes, one wireless controller and the developed LabVIEW program have been applied. Experiments include wireless communication test, stability test, multiple points sensing test, long term monitoring test and comparison with other system have been carried out and are introduced with details.

The wireless communication performance has been tested and is shown in Fig. 6. The placement of sensor node can impact the performance of wireless communication. Among the placement factors, height and distance have been evaluated and the results are shown in Fig. 6 (a) and Fig. 6 (b) respectively.

The height of a sensor node was changed 0.5 m to 1.5 m with a step of 0.5m and RSSI value was measured. In Fig. 6 (a), it can be seen that the RSSI strength decreases while the distance increase in the range from 0 – 50 m. Also, RSSI strength increases with height increase linearly. In Fig. 6 (b), the height of the sensor node was fixed. It can be seen that the RSSI strength decreases with the increase of distance. Therefore, it is essential to place sensor nodes in a relatively high location to achieve better wireless communication. In addition, the RSSI value loss can be accepted able according to the distance test.

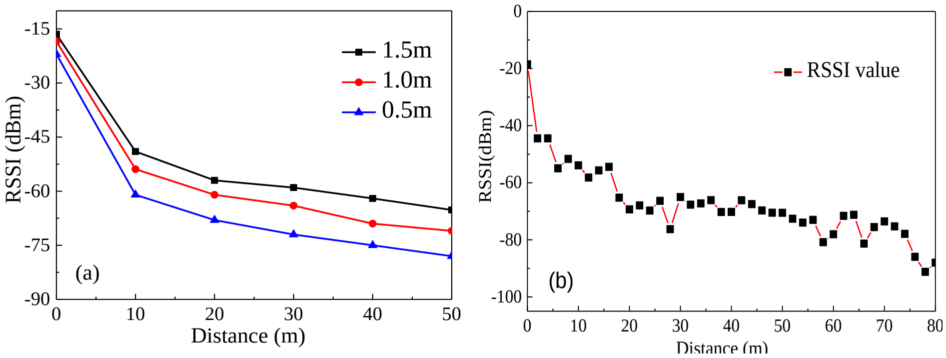


Fig. 6. RSSI value comparison at different height in the distance from 0 m to 50 m (a) and RSSI value attenuation with distance increasing (b)

The stability test was carried out in midnight while the doors and windows were closed, and the in-door temperature was remained constant in a recently decorated laboratory. The HCHO concentration was measured constantly by one sensor node in a period time of 10 minutes and the result is shown in Fig. 7. It can be seen that the HCHO concentration remained in a very small scope. The upper and lower limit of the majority data is from 72 – 75 ppb. This result proves that it is still higher than the safe upper limit and ventilation is essential for this laboratory until the HCHO concentration in atmosphere drop into the safe scope. As shown in the figure, the fluctuation of the HCHO concentration is very slight and this proves the good stability of the HCHO monitoring system.

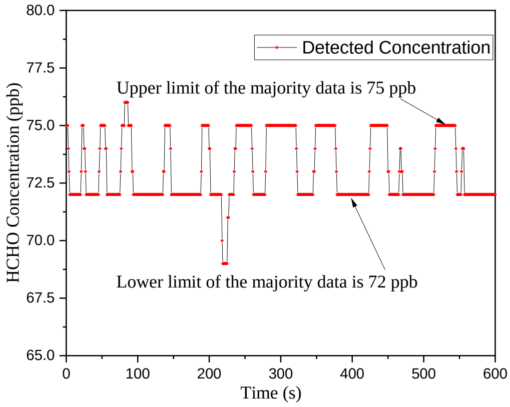


Fig. 7. Stability test of the HCHO system in midnight for a period time of 10 min

The four developed sensor nodes were placed at three corner and the center in the laboratory in order to test the concentration difference. As shown in Fig. 8, four sensor nodes were measuring HCHO concentration at the same time and results were sent to the wireless controller which was plugged in a computer. Then, the wireless controller sent the received data to the proposed LabVIEW program. One can see the concentration measured by the sensor nodes are slightly different, but they are still left in a very shallow concentration scope as show on the right side of the figure.

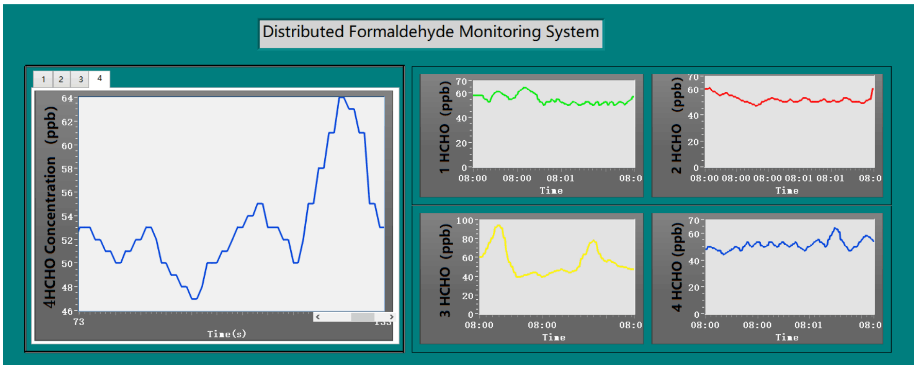


Fig. 8. Developed interface of the distributed formaldehyde monitoring system with 4 sensor nodes working at the same time

The proposed HCHO monitoring system has been compared to another system as referenced [5] in this paper. The table below shows the major difference between the two systems. First of all, the limit of detection is compared as shown in the table. The lower limit of detection is 10 ppb in this paper which is higher than the LOD proposed in reference [5]. However, the proposed system in this paper has been designed for indoor HCHO concentration monitoring purpose. In this way, the LOD of 10 ppb is much lower than the upper limit HCHO concentration according to the standards in many countries which means it can meet the requirement of the design purpose. Then, the response time performance has been compared, for the proposed system, the response time is 6 minutes which is quicker than the other system. Thirdly, the referenced article consumes 20 μL min^{-1} liquid reagent with peristaltic pump and other devices in the system. These devices and materials can be saved in this proposed system due to the detection principle of the electrically driven sensors. The power consumption of the proposed system is very low. For each sensor node, the driving current of electrochemical sensor is about 110 – 460 μA based on different working conditions. The typical power consumption of the main controller and its circuit is about 2.7 – 7 mA and the overall power consumption can be further decreased by adjusting measurement strategy such as adopting power-saving mode or reducing detection frequency. Each sensor node is able to last more than 11 weeks by using three AAA batteries based on the calculations. In addition, size and weight of the proposed system also has advantage compare to the referenced system. And the cost of the proposed is very low due to the reason that the main hardware and software in this system were self-developed. Finally, the propose system also have other advantages including wireless communication, auto-detection ability and distributed detection method which can lead to a more accuracy result than traditional one-point detection method. Therefore, the comparison demonstrates that the propose system can meet the requirements of in-door HCHO detection and there are commercial potential considering its performance and cost-effective features.

Table 1

Comparison between the proposed HCHO system and a commercial system

Refs	LOD (ppb)	Response Time	Reagent Consumption	Weight	Cost	Features
[5]	0.9	10 min	20 (μL min^{-1})	4 kg	High	Acetyl acetone + Fluorimetric microfluidic device
This Paper	10	6 min	None	0.3 kg	Low	Wireless; Auto-detection; Distributed detection

Experiments has been carried out to evaluate the proposed HCHO detection system as shown in Fig. 9. In the period of 5 hours and 40 minutes, one sensor node was activated and HCHO concentration was measured in a sampling rate of 1 second. The experiment can be divided into 3 stages. At the first stage, the sensor node started to work at 5 o’clock in the afternoon. It can be seen that the concentration increased sharply in the first 6 minutes and then became steady when it reached about 48 ppb. At the second stage, the HCHO concentration fluctuated from 45 ppb to 55 ppb due to the influence of its environmental change caused by moving people and ventilation. In this period of time, laboratory staff and students have been working in the lab and they started to leave at about 8 o'clock. Finally, in the last stage from about 8:02 to 10:40, concentration started to increase until it reached another level at about 64 ppb. At the end of the second stage, laboratory staff and students started to leave. Also, the doors and windows were closed. In this way, it can be pointed out that the increase of concentration was caused by the decrease of ventilation. Finally, the ventilation in the laboratory was almost stopped and the HCHO started to accumulate. In this experiment, results demonstrated that the proposed system has the ability to monitor HCHO concentration for further analysis.

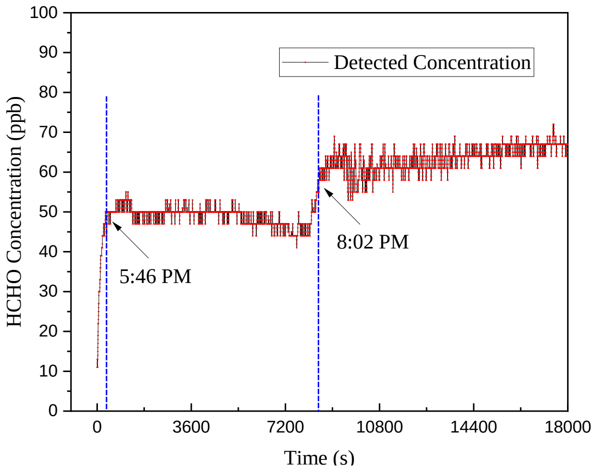


Fig. 9. Detection of HCHO in 5 hours in the laboratory from 5:40 to 10:40 PM

5. Conclusions

In this paper, a distributed wireless formaldehyde monitoring system has been developed and proposed. Experiments were carried out to evaluate its performance. The system consists of four self-developed sensor nodes, one wireless controller and graphical interface developed by using LabVIEW. Each sensor node has a formaldehyde sensor, driving circuits, a wireless module and other essential circuits. The hardware proposed in the system is cost-effective because they were self-developed. The developed LabVIEW program can receive, display and store the detected formaldehyde concentration. Experiments were carried out to evaluate the stability, limit of detection and other performances. Results show that the proposed system is able to monitor in-door HCHO concentration with the advantages including cost-effective, fast response, accurate and convenience. In the future, more experiments will be carried out to improve the system for commercial and research applications.

Acknowledgements

The authors wish to express their gratitude to Jilin Jianzhu University (201810191114), the National Key Technology R&D Program of the Ministry of Science and Technology of China, Province of China and the Education Department of Jilin Province of China (JJKH20180573KJ, JJKH20170240KJ) the Science and Technology Department of Jilin (20180201052SF, 20180201063SF, 20190303114SF), for the generous support of this work.

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