IMPROVED INDOOR FORMALDEHYDE MONITORING SYSTEM USING ENHANCED SELF-DEVELOPED CIRCUITS AND LOCAL OUTLIER FACTOR ALGORITHM

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An indoor distributed formaldehyde monitoring system has been developed with multiple self-developed sensor nodes and wireless communication circuits. Local outlier factor algorithm has been adopted to increase the accuracy of the system. In addition, software has been developed based on LabVIEW for data receiving, data storing, data displaying and remote accessing. Experiments were carried out to evaluate the performance of this improved system. Compared to our previous work, the proposed system exhibits some improvements in performance of formaldehyde sensing ability, software function and quality of wireless communication due to the enhancement of hardware and software in the system.

Keywords: wireless communication sensors, formaldehyde sensing, distributed detection, remote control

With the development of economy and the acceleration of urbanization, people's demand for interior decoration is increasing every year. However, indoor air pollution of new decoration environment causes more and more healthy problems [1-4]. Formaldehyde is a carcinogen confirmed by IARC (International Agency for Research on Cancer). When formaldehyde reaches 0.06-0.07 mg/m^3 in the air, children will have slight asthma. When the concentration reaches 0.1 mg/m^3, there will be peculiar smell and discomfort. When the concentration reaches 0.6 mg/m^3, it can cause throat discomfort or pain [5-9]. When the

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concentration is higher, it can cause nausea and vomiting, cough, chest tightness, asthma and even pulmonary edema. When the concentration reaches 30 mg/m^3, it will cause death. Long term exposure to formaldehyde can lead to respiratory dysfunction and liver toxic lesions, manifested as hepatocyte damage, and there are data show that the increased risk of modern residents suffering from leukemia is closely related to the excessive formaldehyde content. Formaldehyde is widely used in chemical industry, wood industry, textile industry and so on. Many commonly used decoration materials can release formaldehyde. Formaldehyde has been used for room decoration, which becomes the main reason of indoor formaldehyde exceeding the standard [10-13].

At present, the traditional detection methods on the market are mainly chemical analysis and chromatography, which have their own advantages and disadvantages [14-16]. There are many kinds of reagents in chemical analysis, but both of them have disadvantages such as low sensitivity and long reaction time. The chromatographic method has high sensitivity and small interference factors, but the related detection experiment is complex. It needs to extract eluent for further operation. Also, gas chromatography equipment is expensive. Another disadvantage of these systems is that they cannot monitor formaldehyde concentrations in multiple areas at the same time. Therefore, in order to overcome the shortcomings of traditional methods, electrochemical method is used as the detection method [17-19]. Electrochemical method is one of the common methods to detect formaldehyde for indoor air. It calculates the concentration of formaldehyde according to the changes of electric potential and electric quantity produced by the chemical reaction of formaldehyde [20-23]. This method has the characteristics of fast response, high sensitivity, compact size and low detection limit, and is widely used in various occasions [24-27].

In this paper, a distributed formaldehyde detection system has been developed. Compared to our previous work [28], circuits such as wireless communication circuits and sensor control circuits have been improved and software improvements also have been performed to increase the accuracy, stability and convenience of the system. This improved system consists of three sensor nodes with wireless communication function, a wireless receiving circuit and software for receiving and displaying. The hardware part of the system is composed of sensor nodes and wireless receivers, which are used on many occasions. The software is developed by LabVIEW, which can receive data, display data and store data. In addition, it can realize remote monitoring through web publishing function. The system can detect the concentration of HCHO in multiple areas for a long time and can be used in various indoor detection occasions. Therefore, a number of experiments have been carried out in a newly decorated laboratory, including the RSSI strength test, system anti-interference test and system long-term stability test. The results show that the system can meet the requirements of long-term monitoring of HCHO in multi area indoor. In the future, the system will use more wired and wireless sensor nodes to realize the long-term distributed monitoring of HCHO in a larger area of the building.

2. System structure

The developed sensing system can be divided into four logical layers which are software layer, physical layer, system layer and user interface layer as shown in Fig. 1. Firstly, the software layer uses C language programming to control the connection between the sensor node and the receiving module and uses LOF algorithm to eliminate the abnormal points. Secondly, in the physical layer, a number of wireless sensor nodes and a receiving module have been developed. Each sensor node consists of a HCHO sensor, sensor control board with wireless circuit. In our previous work, a wireless module was applied to perform wireless communication. In this paper, the wireless communication circuit has been developed and integrated on the sensor node board. It has been deployed in different areas for multi-point gas detection. The receiving module consists of STM32F103RCT6 and wireless circuit as well. It communicates with multiple nodes and sends data to computer after processing. Thirdly, developed GUI based on LabVIEW is the system layer. It can display the detected data or create a file on the laptop hard disk to store the collected data. Finally, in the user interface layer, users can watch the sensing data and set parameters such as date and time. Data in real time can also be accessed on the internet through web browser by using the web-publishing function of LabVIEW.

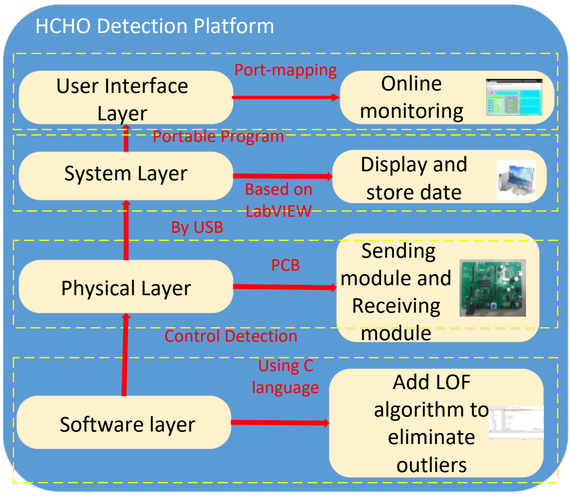

Fig. 1. System structure of formaldehyde detection platform

3. Methods

In this HCHO detection system, the enhanced self-developed circuits can be divided into 2 parts for performing special functions. The first circuit can be named as Board A which is shown in Fig. 2. It can be connected with computers or laptops by using USB ports. It has a main control chip, power supply circuit, UART circuit and the integrated wireless module circuit which is responsible for receiving wireless communication data. The second circuit can be named as Board B. There are 3 same boards of Board B applied in this system. Board B also has MCU, wireless communication circuit and other essential circuits.

As shown in Fig. 2, there are 3 Board B applied in this system to detect HCHO concentration.

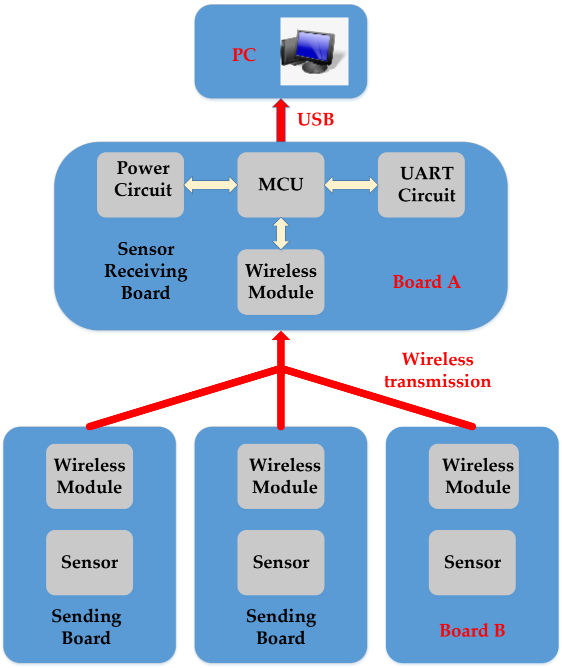

Fig. 2. Functional block diagram of HCHO sensing circuit board

The detected HCHO concentration data can be sent to Board A via wireless transmission. In this way, the detection range can be extended in order to meet the requirement of HCHO monitoring in large site. Another advantage of applying multiple sensors is to avoid accidental detection error of single sensor by using averaged detection result. The collected data can be stored or be sent to computer by Board A. The off-line mode of this system requires no computers and the HCHO concentration can be displayed on LED screens. The on-line mode of the system provides more functions including long time monitoring, graphical display and remote monitoring. This requires the connection between Board A and computer with the installed self-developed monitoring software based on LabVIEW. The sending boards, which can be named as sensor control board or Board B, are responsible to send HCHO concentration data to the receiving board via wireless circuit.

3.1 Hardware Design

Fig. 3 (a) shows the developed receiving circuit, which is also known as board A. Fig. 3 (b) shows the sending circuit, which is applied to send the collected formaldehyde data. Multiple sending modules and receiving modules are connected through the master-slave working mode of ESP8266, which is the wireless controller chip. After receiving data, the host connects to the computer through USB port and sends data to the host computer.

In our previous work, wireless modules were adopted, and the type is SI4438. SI4438 is a high performance, low current, ISM wireless transceiver with a wide voltage supply range that is from 1.8V to 3.6V. It adopts SPI serial protocol and the frequency of wireless communication operates at 433MHz. This module has numerous advantages including low power consumption, high wireless strength and high stability. However, there are two drawbacks of this commercial module applied in this system. Firstly, it has 12 pins for communication and power supply. The connection between the wireless module and control circuit board was not stable due to the reason of loose connection. This is caused by that the center of gravity of this module was not steady. Secondly, it is unable to integrate this module into small device case in the future, because of its height and size.

In this paper, an enhanced wireless circuit has been developed and was integrated as a part of the sensor control board as shown in the left part in Fig. 3 (b). A higher frequency wireless chip, which is ESP8266, has been adopted to perform wireless communication. Its frequency is 2.4GHz. ESP8266 has complete Wi-Fi network function, which can be applied independently or carried on other host MCU as slave. A Nor-FLASH chip is added to the circuit board as an external FLASH memory, which can be directly controlled by ESP8266. The built-in cache can improve the system performance and optimize the storage system. Compared with the previous work, ESP8266 performs better in integration and stabilization. The wireless performance comparison between the new circuit and the commercial module applied in our previous work is shown in later sections in this paper.

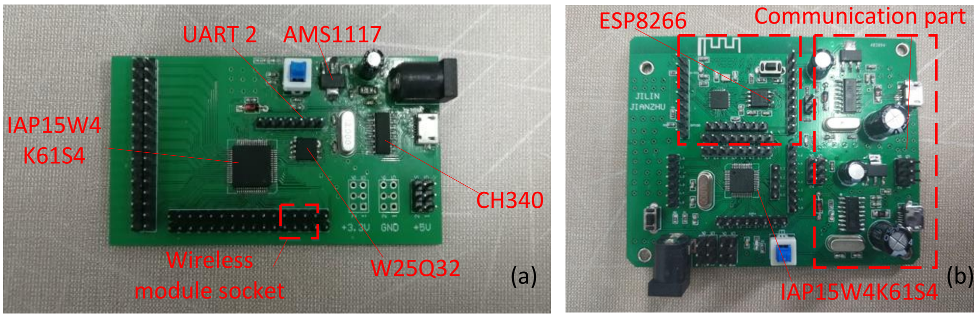

Fig. 3. Receiving circuit board module (a), sending circuit board module (b)

3.2 Algorithm Design

During the experiment, the instrument and sensors may have errors, and data of the sensors may be unstable when it is just powered on or under unexpected noise impact. In this paper, some improvements are made to the software in order to get rid of the error data. Outliers should be handled before data application. Outlier detection algorithms are mainly based on statistics, clustering, classification and density. In this paper, the density-based outlier algorithm has been adopted, which is local outlier factor algorithm (LOF). Its basic idea is to calculate the relative density of each sample and the surrounding samples. The smaller the relative density is, the more likely it is to be an outlier. The key implementation steps of outlier processing are two steps. Firstly, it is essential to calculate the local accessible density of each point according to Equation (1)

$$\mathrm{lrd}_k(p) = \frac{1}{\left(\frac{\sum_{o \in N_k(p)} \mathrm{reach-dist}_k(p, o)}{|N_k(p)|}\right)} \tag{1}$$

$N_K(P)$ is the k-th distance domain of point P, that is, all points within the k-th distance of point P. The reachable distance from point O to point P is expressed by Equation (2), and D (P, O) is the distance from point P to point o.

$$\mathrm{reach-dist}_k(p, o) = \max\{k\text{-}\mathrm{distance}(o), d(p, o)\} \tag{2}$$

The second step is to calculate the local outlier factor of each point shown in equation (3).

$$\mathrm{LOF}_k(p) = \frac{\sum_{o \in N_k(p)} \frac{\mathrm{lrd}_k(o)}{\mathrm{lrd}_k(p)}}{|N_k(p)|} \tag{3}$$

According to the local reachable density, the closer the value is to 1, the closer the density of point P is to be its domain point. The smaller the value is, the denser the relative density of P is. And the greater the value is, the much sparse the point is and the more likely it is to be an outlier. The collected data need to be processed by LOF as shown in Fig. 4.

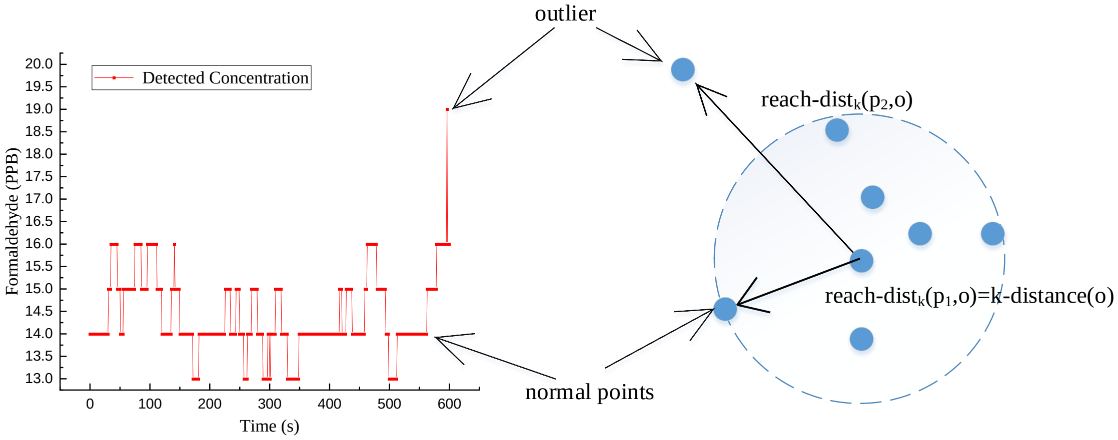

Fig. 4. Schematic diagram of LOF algorithm

The original data needs to be normalized firstly by the sensor receiving circuit. Then the high dimension features of the data set are reduced by principal component analysis, which reduces the calculation amount of the later LOF algorithm, improves the detection efficiency of the system state outliers. Finally, the local outlier factors of all sample points are calculated, and the outlier factor is greater than the set threshold δ. The sample points are classified as outliers. The specific algorithm flow chart is shown in Fig. 5.

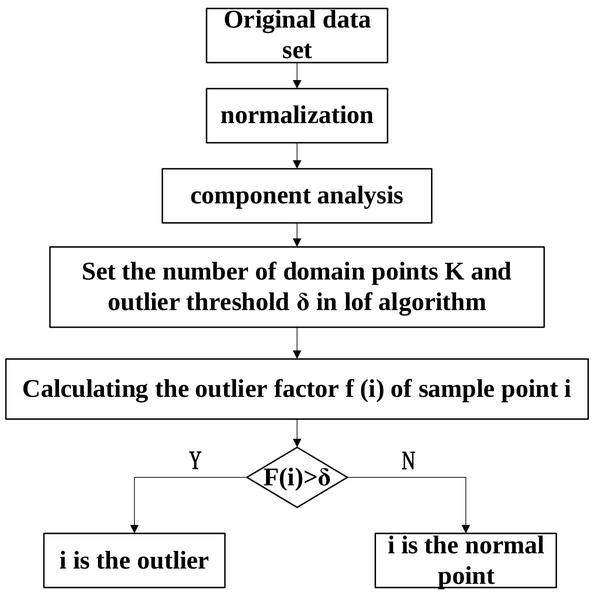

Fig. 5. Flow chart of LOF algorithm

3.3 Antenna Design and Simulation

The HFSS software is used to build the antenna simulation model in order to verify the reliability of the antenna. The initial parameters of the antenna are input into the model, and the PCB material is set as ro4003, which is a double-layer board. The GND layer is on the bottom layer of the PCB. The excitation point connects the GND on the back and the copper foil antenna on the top. The impedance between the excitation point and the matching network should match to 50 ohms. Since the frequency of ESP8266 is 2.41 ~ 2.48 GHz, in order to make the working frequency of the antenna center at 2.45 GHz, the input parameters need to be optimized. The position coordinates of radiating element, cylindrical feed point and circular hole are replaced respectively. Then the influence of the three variables on the resonance point is checked through the frequency sweep setting item. Finally, when the radiating element length of patch antenna is 29.6 mm, the performance meets the expectation. Fig. 6 (a) is the optimized return loss diagram, and Fig. 6 (b) is the three-dimensional gain diagram of the antenna. The performance of the designed antenna is tested in later sections in this paper.

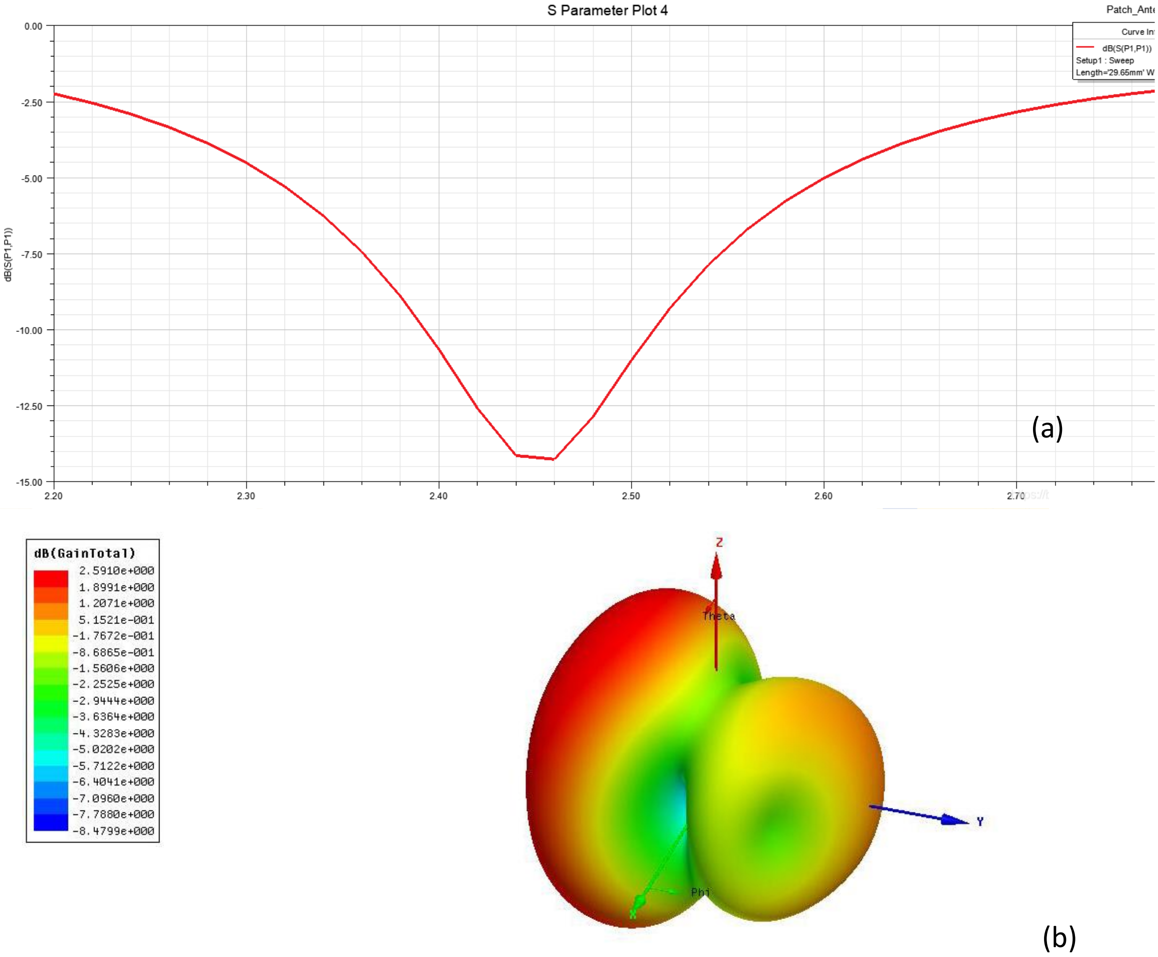

Fig. 6. Optimized return loss diagram (a)
Three-dimensional gain diagram of the antenna (b)

3.4 LabVIEW Interface Design

In order to receive, display, analysis and store HCHO concentration data, software based on LabVIEW has been developed to perform these functions. As shown in Fig. 7, the developed software is accessed remotely by using a PC browser. The front panel of the developed software consists of several zones including windows of the serial port parameters, real time HCHO concentration and long time period monitoring data curves. In this system, three sensors have been adopted and the collected data can be displayed in each window on the right side of the front panel. In the middle of the front panel, three independent windows are deployed to show the real time concentration of HCHO. The front panel can be accessed via internet by using computers or mobiles phones. Besides the front panel, the back panel consists of several parts including the UART module, display VI, data processing and other essential parts.

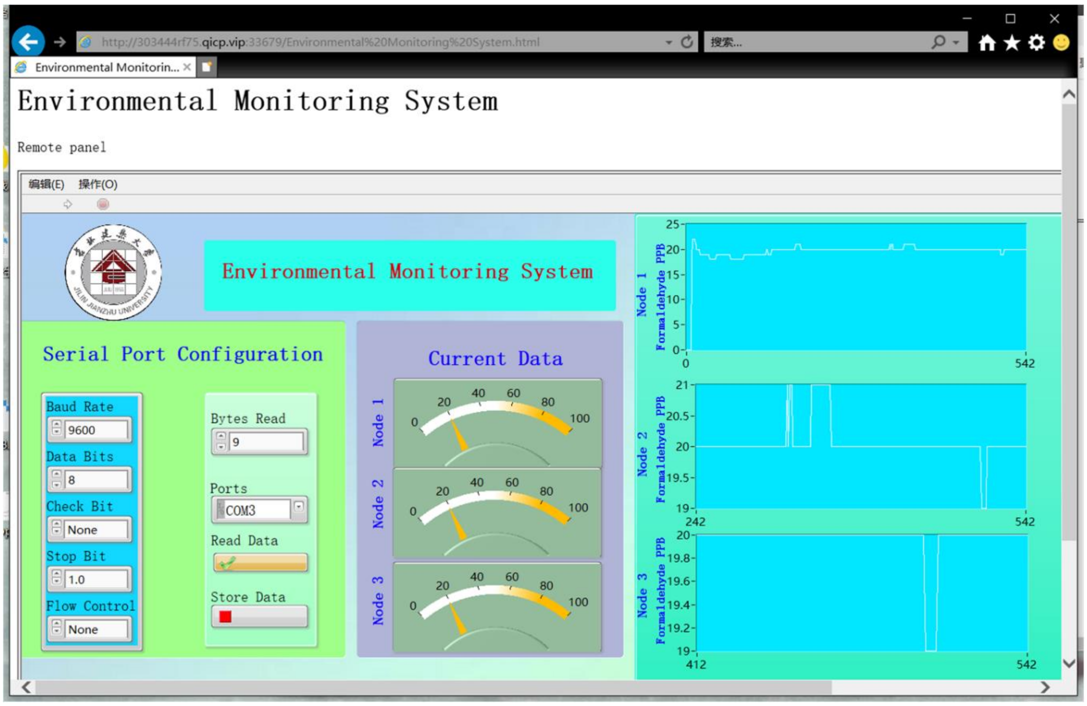

Fig. 7. Interface of indoor environment detection system based on LabVIEW

4. Results and discussion

The signal strength of wireless communication has been evaluated in RSSI measurement tests. Fig. 8 (a) shows the signal strength comparison between the self-designed PCB antenna circuit and the commercial wireless module which was adopted in our previous work. As shown in the figure, when the distance is less than 10 meters, the performance of both circuit is basically the same. As the distance become longer, the signal strength of the on-board antenna has a bigger attenuation as shown in the figure. Though the signal strength is slightly weaker than the commercial module, experiments show that the onboard antenna can also meet the requirements of wireless communication.

Fig. 8 (b) shows the comparison of RSSI value while the sensor node was placed at different height. It can be seen that the blue curve, which demonstrates the sensor node placed at 1.5 m height, has the strongest signal strength among the three curves. This is caused by the reason that the signal strength of the red curve and black curve are blocked and are weakened by indoor facilities such as tables. As shown in the figure, RSSI value decreases as the distance increases, as expected, the performance of the 1.5m curve is still better than the other two curves, which still has -60 dbm signal strength at 10m distance. The test demonstrates that in the indoor environment, the signal faces less barriers at high location, and more barriers at lower location. Therefore, the indoor measurement should be carried out at a high locations to ensure the signal strength.

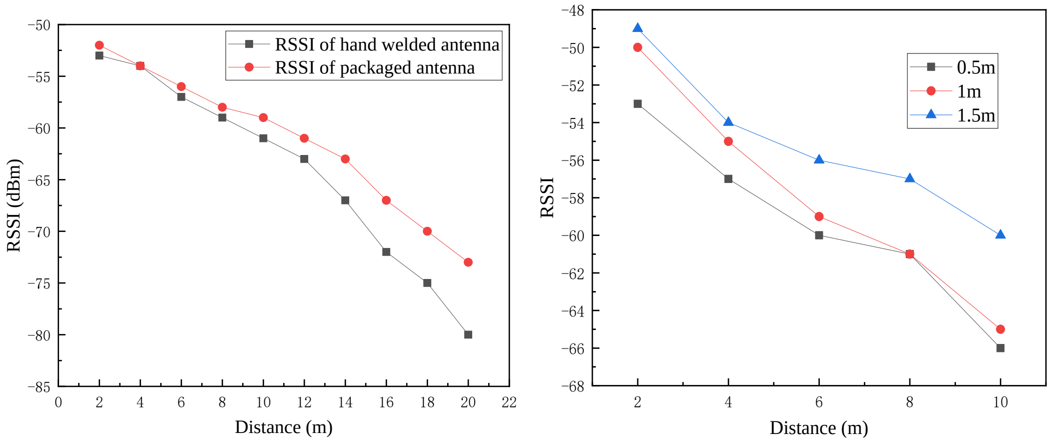

Fig. 8. Drawing antenna signal strength test (a) And RSSI value comparison at different height (b)

Stability test of the developed sensing system has been tested in Fig. 9, the measurement of formaldehyde concentration was performed and the fluctuation was measured in a period time of 10 minutes in order to evaluate the stability of the sensor system.

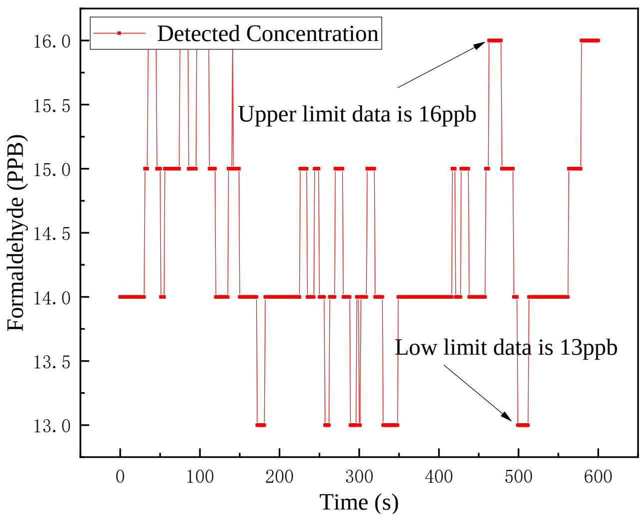

Fig. 9. Stability test of the HCHO system in closed laboratory for a period time

The experiment was conducted at night and in a closed laboratory in order to avoid human interference. It can be seen that the fluctuation is less than 3 ppb which can be caused by air flow and system interferences. The experiment results were shown in the figure below, the variation of the detected concentration was very stable within 10minutes, with a maximum value of 16 ppb and a minimum value of 13 ppb. The experiment proves the stability of the system and this system can be applied for real time measurement.

Long term detection experiments were carried out to evaluate the reliability of the developed HCHO monitoring system. Fig. 10 shows the measurement result of formaldehyde concentration in 24 hours. The system was deployed in a recent decorated laboratory that contents air pollution sources including new furniture and paint walls. During the test, the doors and windows were closed to ensure air tightness. As shown in the figure, the experiment of measuring formaldehyde began at 8 a.m. and it lasts 24 hours. In Fig. 10, it can be seen that the formaldehyde concentration continually increases due to the reason of HCHO emitting and indoor air tightness. It is obvious that after only two hours, the indoor formaldehyde concentration has exceeded 60 ppb which exceeds the national standard of 0.08 mg/m^3. Then, the concentration of formaldehyde continued to increase gradually and reached the peak value of 98 ppb at 2 a.m.. The concentration remained stable in the next five hours until 7 a.m. when windows were opened. The concentration decreased rapidly to the lowest point of 26 ppb in the next half hour and remained stable in the last half hour.

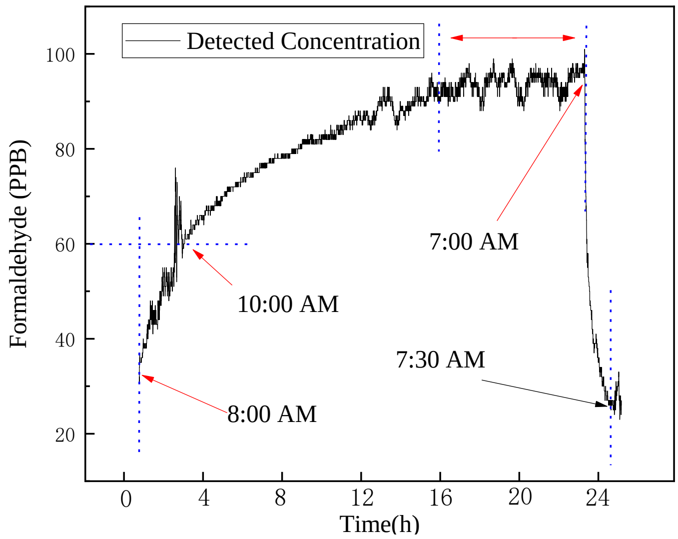

Fig. 10. Stability test of the system in a closed laboratory

In addition, an experiment has been carried out by using the proposed system based on distributed HCHO detection and data analysis. This experiment involves real time gas detection and air flow simulation by using the software of Airpak. The iterations were set as 100 and the model satisfies the convergence requirements as shown in Fig.11 (a). It was performed by monitoring the HCHO concentration in an office room for postgraduate students. The internal structure and facilities are shown in Fig.11 (b). It can be seen that the air flow speed are appeared as different colors as shown in Fig.11 (c). The concentration of HCHO will accumulate in the dark bule areas in the room due the slow air flow speed in these areas. Therefore, it is essential to place several sensor nodes in these areas to monitor the HCHO concentration. Relative research and development work are still ongoing. In our further works, real time detection in more situations and scenarios will be performed by considering factors include room structure, temperature, humidity, air speed, height and so on. Warning signals will appear on the LabVIEW front panel when alerts are necessary.

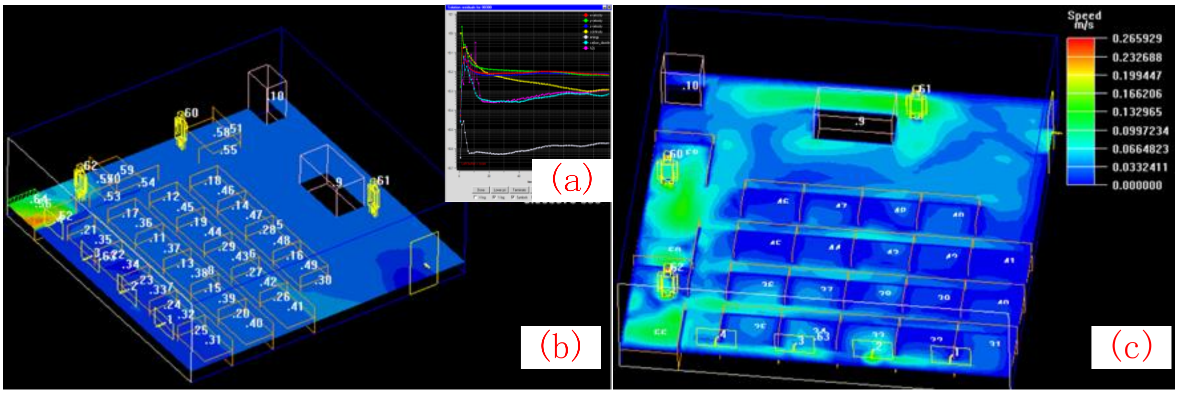

Fig. 11. The iterations settings and convergence test (a), gas concentration in the experimental office room (b) and air flow speed in different areas (c).

5. Conclusions

In this paper, an indoor distributed formaldehyde monitoring system has been developed for hazard gas detection. Compared to our previous work, hardware and software are improved in many ways. In this system, multiple sensors and wireless communication circuits are adopted and there are three sensor nodes which were self-developed for monitoring formaldehyde concentration. Each sensor node consists of a formaldehyde sensor, wireless communication circuit, main control chip and power supply circuit. A receiving board has been developed to receive the detected HCHO concentration data via wireless communicaiton with the sensor nodes. In addition, software has been developed and installed on the computer based on LabVIEW for data receiving, data storing and data displaying. The developed software is also able to store formaldehyde data automatically in Excel files on the hard disk and the front panel can be remotely accessed via internet on other devices such as laptops or mobile phones. LOF algorithm has been adopted to increase the accuracy of the sensing system. Experiments were carried out to evaluate the performance of wireless communication signal strength, sensing stability and longtime detection. Performance of the proposed wireless communication is acceptable in the indoor environment though its RSSI is slightly weaker than commercial modules.Detection results demonstrate that the proposed system is able to detect multiple points in architecture for public health. Based on the long time detection tests, the real time HCHO concentration can be monitored and be recorded by this system for further analysis. An additional experiment has been carried out in an office by combining air flow simulation and distributed gas detection together. In the future, more sensors will be adopted in this system to enhance the detection ability. And more factors will be considered to investigate the sensing performance in more situations and scenarios.

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R E F E R E N C E S

[1] *Y. Song, Z. Wang*, Demethylation of Wheat Straw Alkali Lignin for Application in Phenol Formaldehyde Adhesives. polymers 2016, 8, 209.

[2] *Fredé ric, A.L., Collins, P., Kramer, Z.C.* Phase Space Structures Explain Hydrogen Atom Roaming in Formaldehyde Decomposition. PHYSICAL CHEMISTRY Letters 2015, 6, 4123–4128.

[3] *Bi, A., Yang, S.* Fluorescent probes and materials for detecting formaldehyde: from laboratory to indoor for environmental and health monitoring. RSC Advances 2017, 7, 36421.

[4] *Elhadidy M. M, Hafiz M. G.*, Placement of Leakage Detection Sensors at Pipe Networks JEAS, April 2016, Volume 63, Issue 2 Pages 101–122.

[5] *Descamps, M.N, Bordy, T.* Real-time detection of formaldehyde by a sensor. Sensors and Actuators B: Chemical 2012, 107, 104~108, doi: 10.1016/j.snb.2011.02.032.

[6] *Trafela, S., Zavasnik, J.* Formation of a $Ni(OH)_2$/NiOOH active redox couple on nickel nanowires for formaldehyde detection in alkaline media. Electrochimica Acta 2019, 309, 346~353,

[7] *Zhu, M., Dong, H.* A New Portable Instrument for Online Measurements of Formaldehyde: From Ambient to Mobile Emission Sources. Environmental Science & Technology Letters 2020, 7, 292~297.

[8] *Zhang, J., Liu, X.* Rapid and sensitive detection of formaldehyde based on AC electrokinetic effects. Micro & Nano Letters 2018, 13, 63~68.
[9] *Trocquet, C., Bernhardt, P.* Near Real-Time Monitoring of Formaldehyde in a Low-Energy School Building. atmosphere 2019, 10, 763.
[10] *CHANG, C., GUO, S.* Performance Analysis of Indoor Smart Environmental Control Factors: Using Temperature to Control the Rate of Formaldehyde Emission. IEEE Access 2019, 7, 163749.
[11] *Broek, J., Cerrejon, D.K.* Selective Formaldehyde Detection at ppb in Indoor Air with a Portable Sensor. Hazardous Materials 2020, 399, 123052.
[12] *Zhu, Y., Li, X.* Spatiotemporal Variations in Satellite-Based Formaldehyde (HCHO) in the Beijing-TianjinHebei Region in China from 2005 to 2015. Atmosphere 2018, 9, 5.
[13] *Mujahid, A., Afzal, A.* An Overview of High Frequency Acoustic Sensors—QCMs, SAWs and FBARs—Chemical and Biochemical Applications †. Sensors 2019, 19, 4395.
[14] *Wang, B., Yu, J.* Synthesis and high formaldehyde sensing properties of quasi two-dimensional mesoporous ZnSnO3 nanomaterials. RSC Advances 2019, 9, 14809~14816.
[15] *Park, M., Kim, J.Y.,* Parylene-Coated Polytetrafluoroethylene-MembraneBased Portable Urea Sensor for Real-Time Monitoring of Urea in Peritoneal Dialysate. Sensors 2019, 19, 4560.
[16] *Ganguly, A., Prasad, S.* Passively Addressable Ultra-Low Volume Sweat Chloride Sensor. Sensors 2019, 19, 4590.
[17] *Piro, B., Mattana, G.,* Recent Advances in Skin Chemical Sensors. Sensors 2019, 19, 4376.
[18] *Moro 1, J., Cristofori,* D. Redesigning an Electrochemical MIP Sensor for PFOS: Practicalities and Pitfalls. Sensors 2019, 19, 4433.
[19] *Xu, Y., Sun, Q.,* An Environmentally Aware Scheme of Wireless Sensor Networks for Forest Fire Monitoring and Detection. Future internet 2018, 10, 102.
[20] *Chen, Z.L., Wang, D.,* Wang, XY. et al. Enhanced formaldehyde sensitivity of two-dimensional mesoporous SnO2 by nitrogen-doped graphene quantum dots. Rare Met. 40, 2021, 1561–1570
[21] *Reinbold, R., John, T.,* Spingardi, P. et al. Formaldehyde quantification using ampicillin is not selective. Sci Rep 9, 2019, 18289.
[22] *Wang, D., Lian, F., Yao, S. et al.,* Detection of formaldehyde (HCHO) in solution based on the autocatalytic oxidation reaction of o-phenylenediamine (OPD) induced by silver ions (Ag+). J IRAN CHEM SOC 2021, 18, 3387–3397.
[23] *W. Lu Yu, G. Jun Kuo, X. Jiang Qiang,* QCM formaldehyde sensing materials: Design and sensing mechanism, Sensors and actuators B: chemical, 2019, Vol.293, pp.71-82.
[24] *Zhai, L., Jiang,* W. Intelligent Environment Monitoring System for University Laboratories. Future internet 2018, 10, 110.
[25] *Ali, M.N., Lee, C.S.,* Performance Analysis of On-Demand Scheduling with and without Network Coding in Wireless Broadcast. Future internet 2019, 11, 284.
[26] *Kambourakis, G., Marmol, F.G.* Security and Privacy in Wireless and Mobile Networks. Future internet 2018, 10, 18.

[27] *Ausaf, A., Khan, M.Z.* WLAN Aware Cognitive Medium Access Control Protocol for IoT Applications. Future internet 2020, 12, 11.

[28] *Xue J S, Wei L M*, A Wireless Distributed Formaldehyde Sensing System Using Cost-Effective Self Developed Circuits and Program Series C, Vol. 82, Issue. 4, 2020, pp. 81-92.