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# Research on $CO_2$ Sensor Correcting System Based on ZigBee Net

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**Abstract***:* It designs a signal acquisition system based on ZigBee wireless sensor network, and designs $CO_2$ gas mixing device. In the data processing process, a method to strike a reliable interpolation node based on mathematical statistics is proposed. First, enough static data is processed by Kalman filter to reduce the noise; then the processed static data is analyzed to gain the probability distribution, and then through the goodness of fit test to judge the distribution of the measurement data to obtain reasonable values (mathematical expectation) as the interpolation nodes. Non-equidistant cubic spline interpolation method has been used to gain the sensor characteristic curve. A kind of Carbon dioxide digital sensors has been tested in experiments. Compared with the traditional method of Mean, this method can improve the interpolation accuracy by 13%. Test system has a better economy and ease of use.

**Keywords:** Cubic spline, kalman filter, mathematical statistics, sensor correction, ZigBee net.

## 1. INTRODUCTION

The Measurement of carbon dioxide emissions is important to reduce global greenhouse gas emission. The single sensor measurement data is a fundamental value, which directly affects the accuracy of measurement. In the project, a new type of ultra-low power consumption $CO_2$ sensor is wished to be applied, so the performance should be tested and it's calibration should be done before application. A gas sensor calibration system is needed. Gas sensor test system typically consists of three subsystems: the sensor signal acquisition systems, high-precision gas distribution system, the data processing system [1]. In the study of some existing gas sensor test system, a low cost system has been designed. With the new technology, the new sensor correcting system has better performance:

(1) Using the wireless data acquisition system: the test gas sensor requires a standard gas confined indoor, wireless data collection method can reduce gas leakage and improve system usability.

(2) Kalman filter method combined with statistical signal processing methods improves the accuracy of the measurement.

(3) A suitable theoretical compensation is applied, and the cost of gas distribution system is reduced.

## 2. HARDWARE DESIGN OF THE TEST SYSTEM

### 2.1. Sensor Signal Acquisition System

ZigBee is a protocol based on IEEE802.15.4 wireless communication protocol, the MCU CC2530 is used to accomplish the signal acquisition and data transmission, which has the following advantages:

(1) Low cost single-chip, meeting short distance and low amount data transmission application. Wireless data transmission of the test system does not exceed 10m, the actual amount of every unit is 9 bytes per 2 seconds. The data wireless transmission can be easily executed by the MCU with resistive and capacitive components.

(2) Flexible Number of test nodes. Compared with the system based on data acquisition board, the number of sensor tested by the system based on ZigBee net is more flexible. Compared with the dozen or dozens channels of the board, the max node capacity of ZigBee is 255. In application of batch correction, the flexibility and cost performance is significantly better than that of data acquisition board.

(3) Better applicability. CC2530 MCU has eight 12Bit analog interfaces, and two digital serial interface, and can be easily applied in the test of analog or digital sensors [2-4].

### 2.2. Gas Distribution System

The gas distribution system can create a measurable test conditions for the sensor with adjustable density in the laboratory, and the system's structure is shown in Fig. (**1**).

After pressurize, filter, dehumidification, the high pressure clean air, working as dilution gas, go through a flowmeter (LBZ-F-6, accuracy class 1.5). High purity $CO_2$ gas, filtered and dehumidified, go through another flowmeter (LBZ-F-6, accuracy class 1.5). They are mixed in the test chamber, and regulating the flow can change the volume percentage of carbon dioxide gas mixture. The density of the mixture is measured by a standard meter (Germany Ernie Cox GS10). The chamber volume is about 40L, and over 10 wireless $CO_2$ sensor acquisition

**Table 1. Gas distribution system.**

| Order | Sample Value (% VOL ) | Order | Sample Value (% VOL ) | Order | Sample Value (% VOL ) |
|---|---|---|---|---|---|
| 1 | 0.07 | 6 | 34 | 11 | 70.2 |
| 2 | 15 | 7 | 39.5 | 12 | 75.8 |
| 3 | 22.7 | 8 | 50.3 | 13 | 79.1 |
| 4 | 25.7 | 9 | 59.4 | 14 | 87.9 |
| 5 | 30.7 | 10 | 66.9 | 15 | 98.7 |

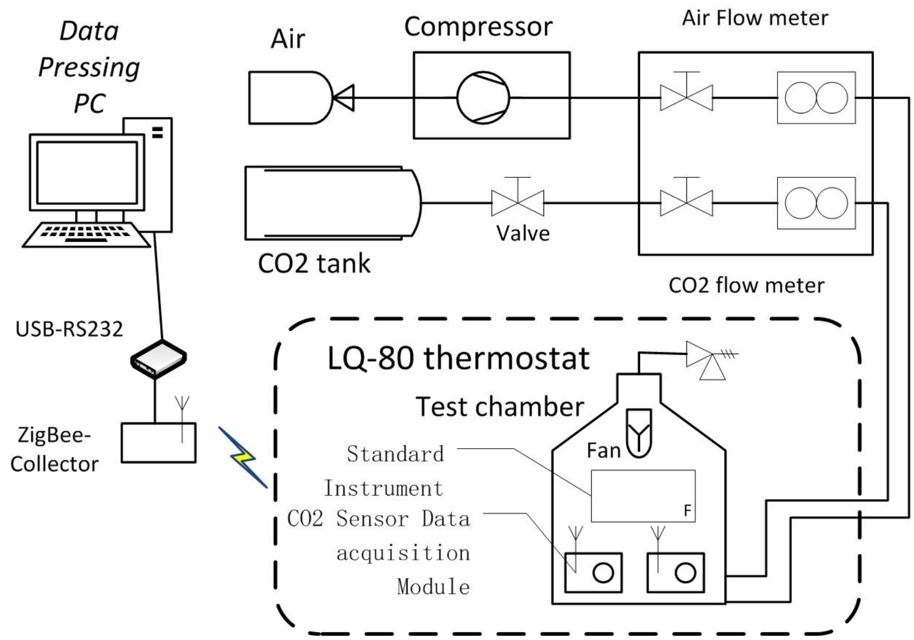


**Fig. (1).** Gas distribution system.

module can be accommodated. The system is placed in a 80L (LQ-80) incubator.

### 2.3. Data Processing System

A computer is applied to process the measure data. The data is collected by a ZigBee collector, and transferred to the PC by RS232 interface. The PC receiver the data through a USB-RS232 interface. The Matlab software reads the data stream from the serial port, and unpacks the data stream and separate out the resulting data from the data frame, filtering, statistics, interpolation and display the final results. There is no high-accuracy high-cost gas distribution system compared with the normal ones, the manual flowmeter can ensure the interval accuracy of the test gas less than 1.5%. The interpolation error can be compensated by adding sample points. Table **1** shows the data of the whole range in a time.

## 3. DATA ACQUISITION AND PROCESSING

### 3.1. Data Acquisition

Within the measuring range (0-100% VOL), by incrementally adjusting the opening of the meter as 15 kinds of proportions, the series of mixed gas with different density can be acquired to test the sensor in the chamber. Its exact concentration measured by a standard instrument. After the $CO_2$ concentration in the chamber becomes stable, the sensor node sampling 2000 points and transmits to the PC for subsequent analysis.

### 3.2. First Step of Data Processing-Denoise

Kalman filtering is a highly efficient recursive filter (autoregressive filter), it can estimated state of the dynamic system from a series of measurements which can not entirely contained in the noise [5-7]. In this test, the Kalman filter is used here to acquire more accurate true measure data.

When the gas in the chamber becomes stabilized, the state equations of Kalman filter is:

$$\begin{cases} \tilde{X}_{\bar{k}} = A\tilde{X}_{k-1} + B\tilde{U}_{k-1} & (1) \\ P_{\bar{k}} = AP_{k-1}A^T + Q & (2) \\ K_k = P_{\bar{k}}H^T(HP_{\bar{k}}H^T + R)^{-1} & (3) \\ \tilde{X}_k = \tilde{X}_{\bar{k}} + K_k(Z_k - H\tilde{X}_{\bar{k}}) & (4) \\ P_k = (I - K_kH)P_{\bar{k}} & (5) \end{cases}$$

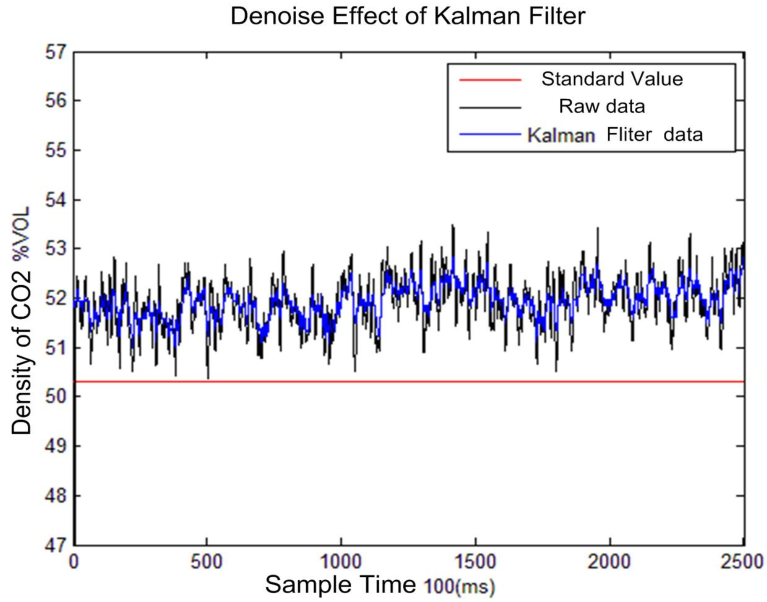


**Fig. (2).** Steady-state data curve before and after the Kalman filter.

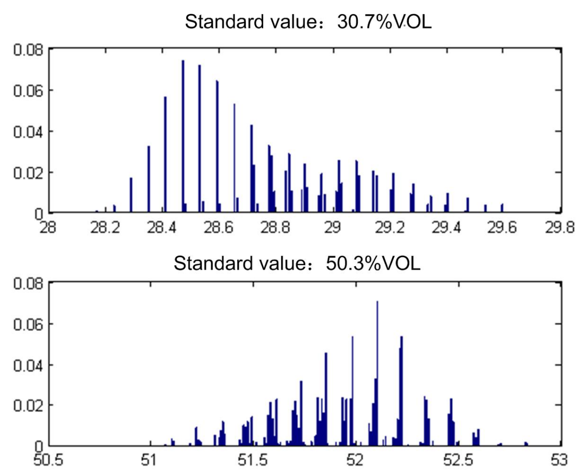


**Fig. (3).** Two probability distribution of the state value.

There is only one state variable, so the state factor $A=1$. There is no input gas, so control factor $B=0$, obeservation gain $H=1$; $Q$ and $R$ is the noise covariance of $CO_2$ density and observation, acquired by experiment test data; $P_{\bar{k}}$ is priori error estimate covariance factor, $P_k$ is posteriori error estimators of the covariance factor; $K_k$ is Kalman gain, calculated by equation.

The effect of denoise is shown in Fig. (**2**), and Kalman filter effectively reduces random errors by 40%.

### 3.3. Second Step of Data Processing-Estimation of the Interpolation Points

Mean value is the most common statistical parameter, commonly used for measurement of central tendency, aiming to determine a balance value of a set of data. The reason of it's wild use is simple. However, the mean value can be easily affected by the outliers, because it takes advantage of all the data information with equal probability. Mathematical expectation is one of the numerical characteristics of random variables. Expected value of a discrete random variable is the sum of the results of the value multiplied by the probability of each value. Mathematical expectation is the weighted average based on probability, so taking mathematical expectation as sample true value is more reliable.

Because of the better data statistical properties of the mathematical expectation, the interpolation points will be calculated in the experiment. Taking the data of 30.7% VOL, 50.3% VOL filtered by Kalman filter as example, the two sample date is denoted as *X1*, *X2*. According to the probability distribution counted by MatLab, the statistical diagram is shown in Fig. (**3**).

Assuming the samples *X1*, *X2* follow the Bernoulli distribution ($p, 0<p<1$).

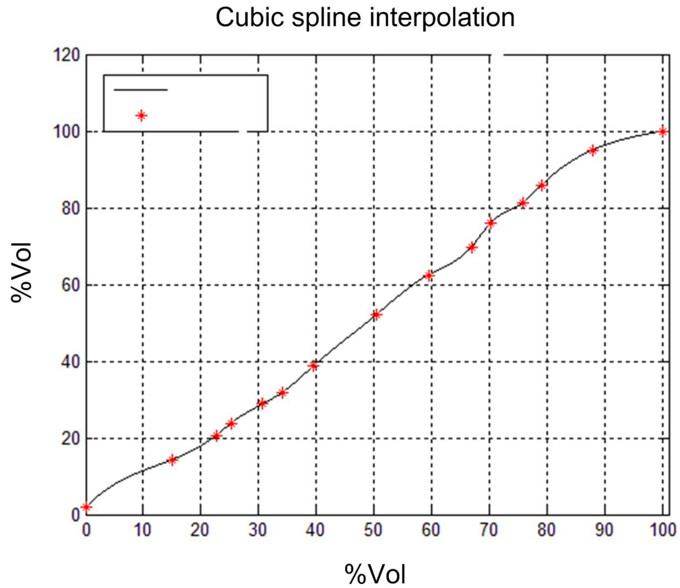


**Fig. (4).** Cubic spline interpolation results.

For *X1*, *p*=1.43e$^{-4}$, the Mathematical Expectation is :

*E(X1)=n*p=28.59%VOL*

Its Mean is:

*X1_=28.41%VOL*

For *X2*, *E(X1)=n*p=52.21%VOL*

*X2_=52.07%VOL*

Other set of data are processed in the same way, the results are taken as interpolation points, as shown in Fig. (**4**).

### 3.4. Third Step of Data Processing-Interpolation of the Sensor Characteristic Curve

Interpolation is an important part of the field of numerical analysis, the way of interpolation is using a small amount of data to construct a more realistic curve. Interpolation methods commonly used in engineering are theoretical straight-line method, the endpoints straight-line method, the best straight-line method, least squares method, spline curve method. In the project, the gas distribution system is not equipped with a precise closed-loop control module (because of high cost), using the manual open-loop control, changing the density of the mixed gas by adjusting the opening degree of the flow meter, so that the equal interval of the test gas cannot be guaranteed, so non-equidistant interpolation method should be considered in the application. About the non-equidistant sampling interpolation methods, cubic spline interpolation has good convergence and stability, and the error can be estimated by the same way of equidistant cubic spline interpolation.

Theorem 1: Set $f(x) \in C^m(\Omega)$ (m = 1,2,3,4), $s(x) \in S^2(\Omega, u)$ is cubic spline function on the division $u$ of $f(x)$: than

$$\left\|(f-s)^{(r)}\right\|_\infty \le \varepsilon_{mr}\left\|f^{(m)}\right\|_\infty h^{m-r}, 0 \le r \le \min(m,3)$$

$h = \max h_i, h_i = x_i - x_{i-1}$ 32870<*i*<*n;* When $r$ = 0, m=3, 4, $\varepsilon_{mr}$=0.3827, 0.013 [7].

The theorem follows a fact: cubic spline interpolation error is related with the high power of maximum length of the interpolation interval [8-11]. For continuous sensor commonly used in engineering applications, the higher order derivatives is generally bounded and small, there is no infinite derivative; the error coefficient $\varepsilon_{mr}$ is also bounded and small. For example, the fourth derivative infinite norm of a function *f(x)* is 1, if the maximum interpolation interval is of 10% of the overall measurement range, according to Theorem 1, the error is less than the overall measuring range of 1/13000. The maximum error of non-equidistant interpolation and equidistant interpolation method have the same maximum estimation error.

For the 15 data listed in Table **1** as an example: the largest partition is 14.93, corresponding to an equivalent number of sampling points:

100/14.93 = 6.69 ≈ 7.

If compared with equal intervals of 15, when *f(x)* is a third-order or fourth-order function, the error of the non-equidistant is 11.4 times or 25.6 times of the equidistant interpolation; if the interval error can be reduced to 20% (for manual flowmeter accuracy level 1.5 class, the accuracy can be guaranteed), the two values are: 1.78, 2.07, which are acceptable in the application.

The theorem further shows that, to ensure the method of non-equidistant interpolation, the number of sampling points should be increased. If the interval error can be ensured, interpolation error can be greatly reduced. This method can reduce the requirements of gas distribution system accuracy, and omitting some precision control components can reduce overall costs.

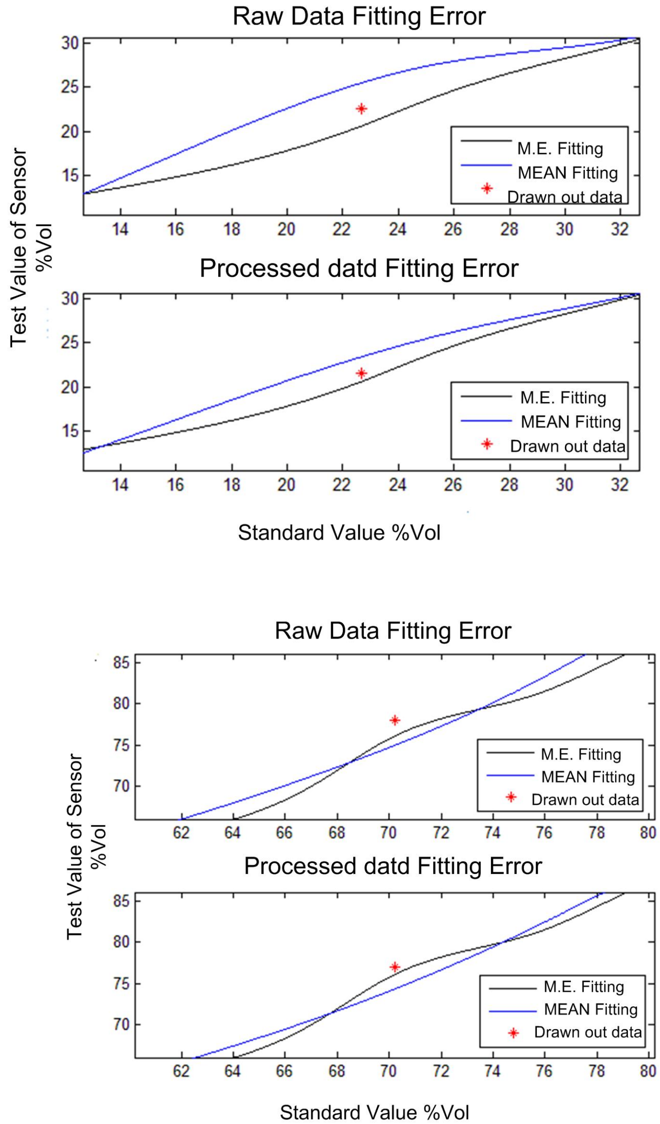


**Fig. (5).** Error of interpolation comparison at density 22.7% and 70.2% VOL.

Since the sensor has a resolution of 0.01, the sampling step is set as 0.005. A total of 15 steady state values of a sensor is collected. The set of 100% data makes no sense for the sensor, it only play a part in the algorithm of interpolation. The cubic spline interpolation of the sensor is shown in Fig. (**4**), that is the parametric curves of the tested sensor in full measuring range.

## 4. CONFIRMATORY ANALYSIS

The gas concentration can be influenced by the temperature and air pressure, in order to exclude the effects of these factors, such a verification method is used:

If the condition $A=\{A1,A2,A3,A4,A5\}$ is a necessary and sufficient condition constitutes an event *S*, conditions *A* is subject to the conditions of $B(t)=\{B1(t),B2(t),B3(t),B4(t)\}$. Now construct a mappings *f(x)* from condition *A* to *S*. To examine reliability of *f(x)*, construct a new event *S′* based on a difference set of *A* and $A_k$ , and find out a similar condition $A_k'$ .Comparing the similarity of *S* and *S′* or *A* and *A′* the reliability of *f(x)* can be test.

The latter method is taken in the examining experiment. Specifically, draw out one date $x_k$ from the 15 points, and the remaining 14 points constitute a new collection, and interpolate a new cubic curve based on new collection. Taking the value $\Delta x_k=|x_k - x_{spline}|$ as the basis of similarity evaluation. Comparing the bigness of $\Delta x$ of the curve based on the mathematics expectation and mean, the closer one to the real curve is better. In the experiment, the data of $x_3$=22.7 and $x_6$=70.2 has been drown out respectively, and fitting results is shown in Fig. (**5**).

The $\Delta x_k|_3$ before and after the filtering are 0.78 and 0.68. For $\Delta x_k|_6$ the value is 0.66 and 0.56. The smaller value proves

**Table 2. Error Analysis Table of the whole range.**

| $x_k$ | $\Delta x_{\_mean}$ | $\Delta x_{\_K+S}$ | D | $x_k$ | $\Delta x_{\_mean}$ | $\Delta x_{\_K+S}$ | D |
|---|---|---|---|---|---|---|---|
| 15 | 2.06 | 1.1 | 22.63 | 50.3 | 1.66 | 1.26 | 19.9 |
| 22.7 | 1.78 | 1.05 | 10.2 | 59.4 | 1.44 | 1.45 | 16.6 |
| 25.2 | 1.47 | 0.91 | 8 | 66.9 | 2.03 | 1.31 | 10.8 |
| 30.7 | 1.43 | 1.43 | 8.8 | 70.2 | 1.85 | 1.24 | 8.9 |
| 34 | 1.5 | 1.02 | 8.8 | 75.8 | 1.52 | 1.17 | 8.9 |
| 39.5 | 1.72 | 1.58 | 16.3 | 79.1 | 1.07 | 0.87 | 12.1 |

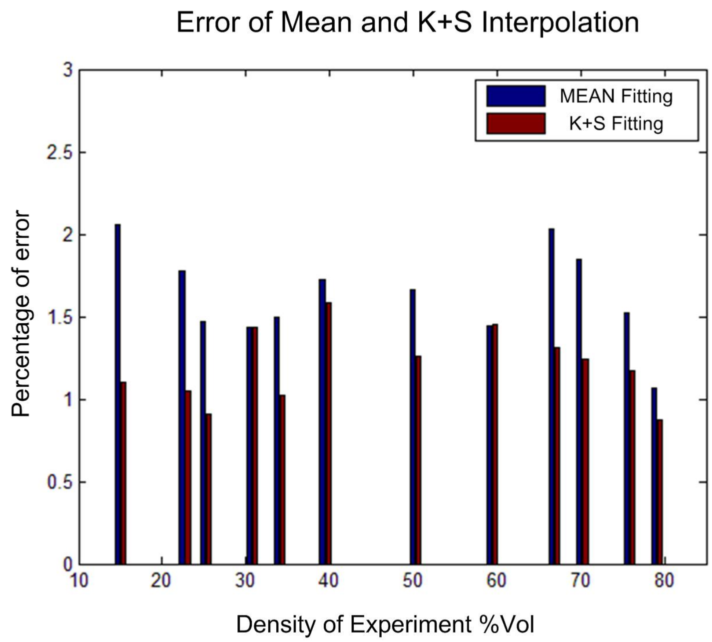


**Fig. (6).** Error bar graph of two ways interpolation.

that the Kalman filter combined with statics reduces the error of interpolation.

In the whole range , choosing $x_2 \sim x_{13}$ 12 points, the interpolation interval is $D = |x_{k+1} - x_{k-1}|$, the error data and the interval is listed in the Table **2**, and the bar graph is shown in Fig. (**6**).

Comparing and analyzing the data in Table **2** and bar graph of Fig. (**6**), nearly all the error of interpolation points are reduced. A more accurate interpolation of the results obtained by Kalman filter combined with mathematical expectation estimation; Results of experiment shows that compared with the mean value, the new method adopted in the practice the error can be effectively reduced by 13%; Application of Kalman filter can greatly reduce the noise of the raw data, and the mathematical expectation can estimate the more scientific interpolation points.

## CONCLUSION

The data acquiring module based on ZigBee technology is easier to use because of the networking technology, wireless transmission, automatic networking features; and more economical for its low-cost single chip compared with the data acquiring board. In the case of high-precision calibration curve requirements, Kalman filtering combined with statistical method is a more accurate estimate method of the interpolation nodes. Using cubic spline interpolation, it reduce the accuracy requirements of the gas distribution system, and reduce the cost of the data acquisition device in the test system. Results of error comparing show that the method applied in the calibration process is more accurate, and improve sensor accuracy and measure accuracy of the overall $CO_2$ emissions. The tested ultra-low power consumption $CO_2$ sensor is base on the infrared ray, and can be applied in the low temperature to -20℃. Small amount of sensor

(10 units) sample of test shows the difference is less than 2%. With very low power consumption, the sensor is better than some similar products. Because of its combination with wireless sensor network technology [12], the application of long-lasting battery $CO_2$ gas concentration monitoring and management system has key technology foundation.

## CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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## REFERENCES

[1] Y. Cu, and Z. Tang, "Design of high precision dynamic testing system of gas sensor", *Journal of Instrument*, vol. 31, pp. 2180-2184, 2010.

[2] D.M. Han, and J.H. Lim, "Smart home energy management system using IEEE 802.15.4 and ZigBee", *IEEE Transactions on Consumer Electronics*, vol. 56, no. 3, pp.1403-1410, 2010.

[3] Z. Alliance, "Smart energy profile specification", Version1.0, pp.18-20, 2009.

[4] J. Son, "Measurement and control system based on CC2530 for greenhouse", In: *International Conference on Electrical Cntrol Engineering (ICECE)*, Yichang: China, 2001, pp. 4565-4567.

[5] M. Den, Z. Zeng, and Y. Xiong, "A fitting approach of the temperature characteristic curve of sensor based on the recursive least squares algorithm", *Future Intelligent Information Systems*, vol. 86, pp. 505-510, 2011.

[6] R.E. Kalman, "A new approach to linear filtering and prediction problems", *Journal of Basic Engineering*, vol. 82, pp. 35-45, 1960.

[7] K. Wang, "Practical approaches to kalman filtering with time-correlated measurement errors", *IEEE Transactions on Aerospace And Electronic Systems*, vol. 48, no. 2, pp.1669-1681, 2012.

[8] W.L. Xie, "The error analysis of cubic spline function", *Journal of Jiang Nan College*, vol. 15, pp. 103-106, 2012.

[9] D. Cao, and H. Wang,"Numberic stability of interpolation functions of cubic spline", *Journal of China University of Mining & Technology,* vol. 2, pp. 213-216, 2001.

[10] T. Wen, "Error estimation of cubic spline", *Computational Mathematics*, no. 2, pp. 10-15, 1982.

[11] W.L. Chen, "Application of cubic spline interpolation on the fitting in engineering", *Journal of Central China Normal University*, vol. 38, pp. 418-422, 2004.

[12] H. Liang, "A solar energy battery monitor system based on wireless sensor net", *Automation Equipment of Power*, vol. 30, pp. 125-128, 2009.

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