RESEARCH ON ENVIRONMENTAL MONITORING AND COMPREHENSIVE EVALUATION SYSTEM OF PIG HOUSE BASED ON INTERNET OF THINGS TECHNOLOGY

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基于物联网技术的猪舍环境监测与综合评价系统研究

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ABSTRACT

To address the issues of low precision and high cost in pig house environmental monitoring, an Internet of Things (IoT)-based pig house environmental monitoring system is proposed in this study. The system utilizes ESP32 as the main control chip of each sensor node, which is constructed in a star topology structure, realizing data transmission by using wireless communication technology. By incorporating the median filtering function and the Kalman filtering algorithm to perform data fusion of the same type of environmental parameters, the accuracy of the data is ensured. Based on the environmental suitability requirements of pigs, an evaluation index system for pig house environmental suitability is established, and comprehensive weight calculations are carried out by combining the entropy weight method and the improved analytic hierarchy process. Simulation experimental results demonstrate that the error of the temperature data after Kalman filtering fusion is merely 0.12%, fulfilling the monitoring accuracy requirements. The system can precisely evaluate the environmental suitability of pig houses, and it is applicable for monitoring pig house environments.

摘要

为解决猪舍环境监测精度低和成本高等问题，本研究提出了一种基于物联网的猪舍环境监测系统。系统采用 ESP32 作为各传感器节点的主控芯片，并通过星型拓扑结构搭建，利用无线通信技术实现数据传输。通过引入中值滤波函数和卡尔曼滤波算法对同类型的环境参数进行数据融合，确保数据准确性。基于猪只对环境的适宜度要求，构建了猪舍环境适宜度评价指标体系，并结合熵权法与改进层次分析法进行综合权重计算。仿真实验结果表明，经过卡尔曼滤波融合后的温度数据误差仅为 0.12%，满足监测精度要求。系统能够准确评价猪舍环境适宜度，适用于猪舍环境监测。

INTRODUCTION

With the transformation of the agricultural industry structure, pig farming industry is evolving towards large-scale, intensive, and industrialized operations. This development is of great significance for optimizing the rural economic structure, improving agricultural efficiency, and increasing farmers' income (*Han et al., 2010*). However, currently, small and medium-sized pig houses still face challenges such as difficulties in implementing environmental monitoring technology and high monitoring costs. The quality of pig house environment is a crucial factor in ensuring the healthy breeding of pigs, directly influencing their growth, development, and reproductive ability *(Spinka et al., 2017)*. It will lead to serious consequences, such as diseases and economic losses to farmers, if pigs grow in harsh environments for a long time *(Chen et al., 2020; Li et al., 2023)*. Therefore, monitoring various parameters of the pigs' growth environment and improving the management level of pig farm environmental quality are of great significance for promoting the sustainable development of global pig farming industry *(Li et al., 2024; Wang et al., 2024)*.

Numerous scholars have conducted research on the intelligent monitoring and control of pig house environmental quality to overcome existing problems. For example, *Zeng et al., (2020*), investigated a wireless multi-point, multi-source remote monitoring system for pig house environments, which can rapidly perceive the spatiotemporal distribution characteristics of pig house environmental parameters, providing valuable references for optimizing pig house environmental control.

Huang et al., (2022), employed narrowband Internet of Things (IoT) and cloud platform technics to achieve remote monitoring and real-time regulation of multiple environmental factors such as temperature within pig house, effectively ensuring welfare of pigs and offering new design solutions for intelligent monitoring systems in pig farming. Nevertheless, these studies do not explore pigs' adaptability to pig house environment. Regarding the adaptability of pigs to pig house environment, many scholars have also carried out research *(Xie et al., 2024)*. For instance, *Chen et al., (2022),* utilized an improved analytic hierarchy process combined with fuzzy comprehensive evaluation to establish a comprehensive evaluation system for pig house environment, which can evaluate the suitability of pig house environment in real-time and provide a good design solution for precise regulation and early warning of pig house environment. *Wang et al., (2023*), applied a fuzzy comprehensive evaluation method to study an IoT-based environmental suitability evaluation system for fattening pig houses. This system can simultaneously collect data on multiple environmental factors in pig house and perform transmission, analysis, and display of these environmental data.

However, most of these studies typically adopt a single analytic hierarchy process (AHP) or entropy weight method for weight calculation, failing to comprehensively consider the deviation of subjective weight calculation methods and the one-sidedness of objective weight calculation methods (*Xie et al., 2016; Chi et al., 2022; Xie et al., 2024; Liu et al., 2024*).

To solve the aforementioned problem, this paper focuses on pig house environmental information monitoring as the research subject and combines Internet of Things (IoT) technology, wireless communication technology, and others to design an IoT-based pig house environment monitoring and application system (*Gao et al., 2016; Bai et al., 2019; Zhou et al., 2021; Wang et al., 2024; Wang et al., 2024*). This system can remotely monitor environmental information such as temperature and relative humidity within pig house simultaneously. Additionally, to evaluate pig house environment more scientifically, the weight coefficient of the environmental evaluation index of pig house is calculated by integrating the subjective weight calculation method and the objective weight calculation method, thereby reducing the deviation and one-sidedness of the environmental evaluation. Finally, the fuzzy comprehensive evaluation method is utilized to assess the suitability of pig house environmental data. The suitability evaluation results can provide decision support for the precise regulation of pig house environment.

MATERIALS AND METHODS

Overall system plan

The experimental pig house is located at 11.32°E longitude and 37.19°N latitude. The internal view of the pig house is shown in Figure 1. The Internet of Things system for remote monitoring of the pig house environment mainly consists of three parts: the Information acquisition and perception layer, the Information wireless transmission layer, and the information processing and application layer. The overall structure of the system is illustrated in Figure 2. The pig house is monitored at 20 different points, each equipped with a set of sensor nodes. Thus, a total of 20 sets of sensor nodes and one set of sink node are installed in the monitoring area of the pig house.

Fig. 1 – Internal picture of pig house

Each set of sensor nodes is composed of the required environmental factor sensor, a data transmission interface, a main control chip and other structures, and it is powered by an independent power supply. These sensor nodes collect data on environmental factors within the pig house using their onboard main control chips and transmit the data via Wi-Fi to the sink node. The sink node performs data fusion on the received information from the sensor nodes and conducts corresponding evaluations based on a suitability evaluation model for the pig house environment, thereby enabling the analysis of environmental information throughout the entire pig house. Finally, the fused environmental factor data such as temperature and humidity are transmitted to the cloud platform via Wi-Fi, and the cloud platform uses the HTTP data transmission protocol to send this information to a WeChat mini-program, allowing users to view and access real-time environmental information about the pig house through either a PC or a mobile device.

ESP32 is used as the main control chip of the system. ESP32, which integrates a TCP/IP protocol stack enabling direct connection to Wi-Fi networks and also functioning as a hotspot, is utilized as the main control chip of this system. The sink node operates in softAP+Station mode, in this system. In this mode, the ESP32 main control chip can be used both as a terminal node and as a wireless access point, meeting the functional requirements of the sink node. Additionally, the ESP32 provides functions such as IIC interface, GPIO interface, UART serial port, and ADC interface, which can satisfy design requirements.

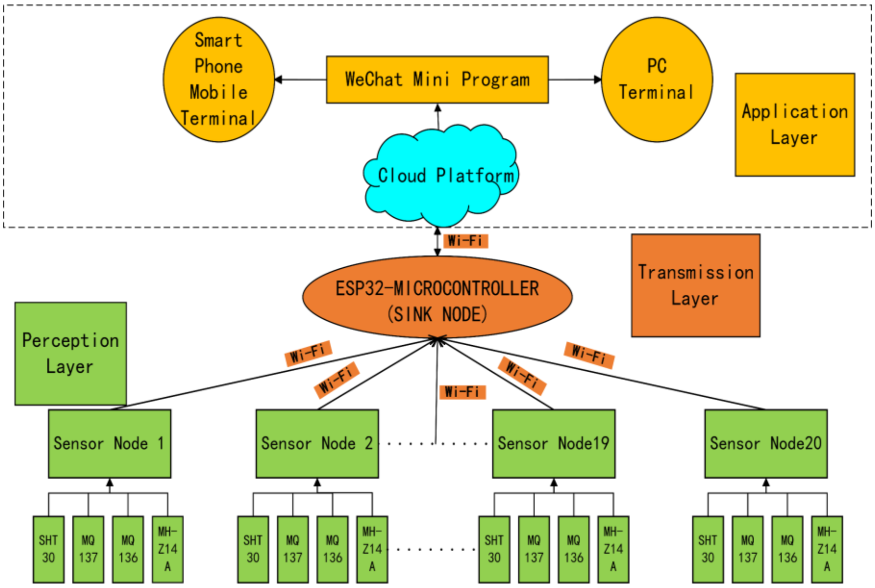

Fig. 2 – Overall system structure

System hardware design

(1) System sensor nodes hardware design

The temperature and relative humidity collection module adopts the SHT30 temperature and humidity sensor, which exhibits higher stability and reliability compared to other similar sensors. Its temperature measurement range is from -40°C to 125°C with an error margin of ±0.2°C, and the relative humidity measurement range is from 0%RH to 100%RH with an error margin of ±2%RH. It is connected to the ESP32 via an IIC interface. The ammonia gas collection module uses the MQ137 ammonia gas sensor, with a detection range of 5×10^{-6} to 5×10^{-4} mg/m^3. The hydrogen sulfide collection module employs the MQ136 hydrogen sulfide sensor, with a detection range of 10^{-6} to 10^{-4} mg/m^3. The carbon dioxide collection module utilizes the MH-Z14A carbon dioxide sensor, with a detection range of 0 to 10^{-2} mg/m^3. The environmental information data within the pig house is processed by the ESP32 microcontroller and transmitted to the sink node via Wi-Fi. The connection circuit between the ESP32 MCU and the sensor is shown in Figure 3.

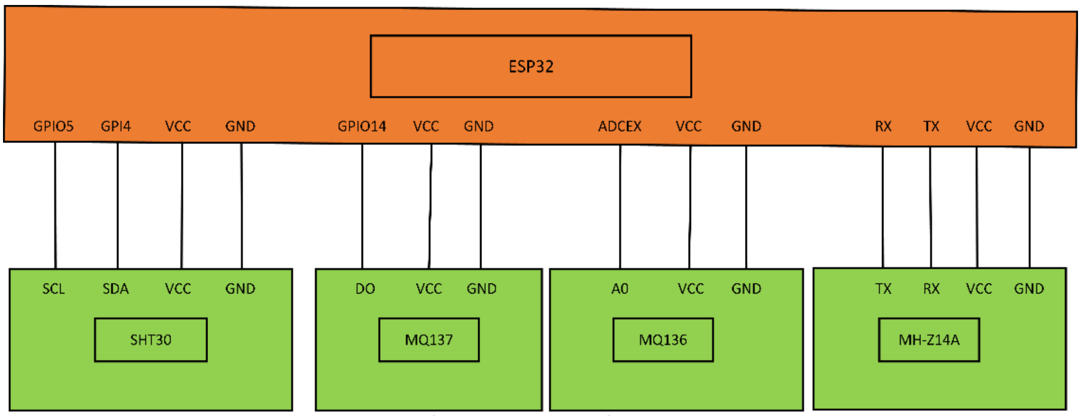

Fig. 3 – Interface between ESP32 and sensor

(2) System sink node hardware design

The main function of the sink node is to receive environmental information parameters collected from sensor nodes and it optimizes and fuses environmental data of the same type using a median filtering function and a Kalman filter algorithm. Meanwhile, it can display the current environmental information inside the pig house and assess the current environment of the pig house in combination with a comprehensive evaluation model. The sink node adopts an ESP32 single-chip microcomputer along with an ILI9488 3.5-inch TFT display screen, allowing real-time viewing of the current environmental parameters on the display screen. The connection circuit between the ESP32 MCU and the TFT display is shown in Figure 4.

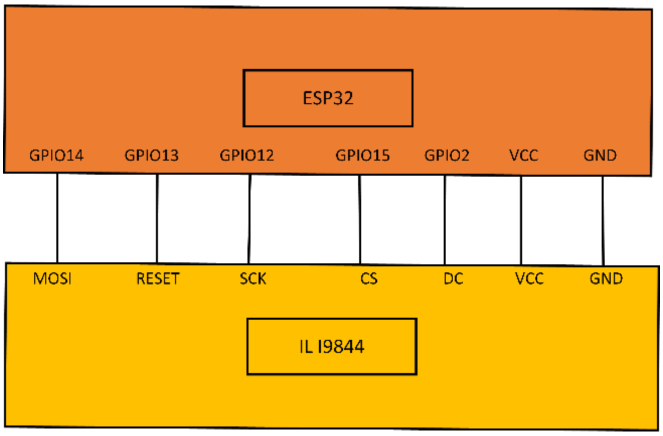

Fig. 4 – Schematic diagram of ESP32 MCU and ILI9488 display

Environmental parameter acquisition algorithm design

This paper's fusion algorithm is based on data collected by environmental parameter acquisition sensors, including temperature, humidity, ammonia gas concentration, hydrogen sulfide concentration, and carbon dioxide concentration. Before fusion, a median filter function is used to optimize the data and reduce the impact of random factors. Subsequently, a Kalman filter algorithm is applied to fuse the environmental data collected from the pig house. The main steps of the Kalman filter algorithm are as follows:

The system's current state prediction equation is as follows:

$$\hat{x}_{k/k-1} = A_{k-1/k-1}\hat{x}_{k-1/k-1} \tag{1}$$

where:

$\hat{x}_{k/k-1}$ is the predicted result of the system state at the current moment, $A_{k-1/k-1}$ is the system state transition matrix, and $\hat{x}_{k-1/k-1}$ is the optimal system state estimate from the previous moment.

There is a certain error between the predicted value and the true value, and the error covariance matrix equation is as follows:

$$P_{k/k-1} = A_{k-1/k-1}P_{k-1/k-1}A^{T}_{k-1/k-1} + Q_{k/k} \tag{2}$$

where:

$P_{k/k-1}$ is the system prediction state covariance matrix at the current moment, $P_{k-1/k-1}$ is the optimal prediction state covariance matrix from the previous moment, and $Q_{k/k}$ is the process noise covariance matrix.

The Kalman Gain equation is as follows:

$$K_{k/k} = P_{k/k-1}C^{T}_{k/k}(C_{k/k}P_{k/k-1}C^{T}_{k/k} + R_{k/k})^{-1} \tag{3}$$

where:

$K_{k/k}$ is the Kalman Gain, $C_{k/k}$ is the measurement matrix, and $R_{k/k}$ is the measurement noise covariance matrix.

The optimal state estimation equation for the system at the current moment is as follows.

$$\hat{x}_{k/k} = \hat{x}_{k/k-1} + K_{k/k}(y_{k/k} - C_{k/k}\hat{x}_{k/k-1}) \tag{4}$$

where:

$\hat{x}_{k/k}$ is the optimal state estimate at the current moment, and $y_{k/k}$ is the sensor measurement value at the current moment.

The covariance matrix update equation for the current moment is as follows:

$$P_{k/k} = [I - K_{k/k}C_{k/k}]P_{k/k-1} \tag{5}$$

where:

$P_{k/k}$ is the covariance matrix of the optimal state estimate at the current moment, and I is the identity matrix.

ENVIRONMENTAL SUITABILITY FUZZY COMPREHENSIVE EVALUATION MODEL

The comprehensive evaluation of the pig house is mainly carried out through sink node. The sink node receives data from sensor nodes and performs data fusion. Based on the fused values of various environmental parameters, a comprehensive weight calculation is performed by combining the entropy weight method and an improved analytic hierarchy process. Then, based on the data fusion values and weight set from the sink node, an evaluation of the suitability of the pig house environment is made.

Construction of the evaluation index system

The environmental factors that have the most significant impact on the growth, development, and reproduction of pigs include environmental temperature, relative humidity, ammonia gas concentration, carbon dioxide concentration, and hydrogen sulfide concentration. Therefore, this paper selects these five environmental parameters as the evaluation indicators for pig house environmental suitability. The degree of suitability is represented by 3 levels: Suitable (C), Relatively Suitable (M), and Unsuitable (B). Based on the environmental parameters of large-scale pig farms and the environmental management standards issued by the state, a pig house environmental evaluation index system is established, as shown in Table 1 *(GB/T 17824.3-2008)*.

Table 1

Environmental evaluation index system of pig house

Evaluation result set	Factor set				
	Temperature / °C	Relative Humidity/ %	Carbon dioxide / (mg·m^{-3})	Ammonia gas / (mg·m^{-3})	Sulfuretted hydrogen / (mg·m^{-3})
Suitable	18~22	60~70	0~1000	0~2	0~2
Relatively suitable	16~18 **or** 22~27	50~60 **or** 70~80	1100~1200	5~10	4~6
Unsuitable	>27 **or** <16	>80 **or** <50	>1300	>20	>10

Evaluation modeling steps

The evaluation of pig house environmental suitability is conducted using a fuzzy comprehensive evaluation method that combines the entropy weight method, the improved analytic hierarchy process, and fuzzy set. The modeling steps are as follows:

(1) Determine the factor set: Based on the established evaluation index system, determine the environmental factors that have the greatest impact on the healthy growth of pigs, and establish the evaluation factor set $I=\{u_1,u_2,u_3,u_4,u_5\}$. These include $u_1=$ temperature, $u_2=$ relative humidity, $u_3=$ ammonia gas concentration, $u_4=$ carbon dioxide concentration, and $u_5=$ hydrogen sulfide concentration.

(2) Determine the evaluation result set: The evaluation result set is divided into three levels, denoted as $D=\{d_1,d_2,d_3\}$, where d_1 is Suitable (C), d_2 is Relatively Suitable (M), and d_3 is Unsuitable (B).

(3) Establish the membership matrix and conduct single-factor evaluation: According to the evaluation standards for each indicator, determine the membership functions for each indicator. Use these membership functions to calculate the membership matrices for the five environmental factors: temperature, relative humidity, ammonia gas concentration, carbon dioxide concentration, and hydrogen sulfide concentration, corresponding to H_1, H_2, H_3, H_4 and H_5. Combine these single-factor membership matrices to obtain the overall membership matrix H. Evaluate the pig house environment based on the maximum membership principle. The form of the membership matrix H is as follows:

$$H=\begin{bmatrix}H_1\\H_2\\H_3\\H_4\\H_5\end{bmatrix}=\begin{bmatrix}h_{11}&h_{12}&h_{13}\\h_{21}&h_{22}&h_{23}\\h_{31}&h_{32}&h_{33}\\h_{41}&h_{42}&h_{43}\\h_{51}&h_{52}&h_{53}\end{bmatrix}=(h_{ij})_{5\times3} \quad (6)$$

where:

h_{ij} is the membership degree of the i-th evaluation indicator belonging to the j-th level.

(4) The entropy weight method and an improved analytic hierarchy process (AHP) are used to determine the index weights. First, the collected data is standardized, and then the entropy values and information entropy redundancy of various environmental parameters within the pig house are calculated.

Based on this, the objective weight coefficient for each environmental parameter is derived. The improved AHP uses a 1-9 scales method for pairwise comparisons to obtain the importance ranking index of each environmental factor, establishing a comparison matrix. It then constructs an indirect judgment matrix and optimizes it to find the maximum eigenvalue and eigenvector, which are normalized to obtain the subjective weight coefficients. The subjective and objective weight coefficients are combined to obtain the comprehensive weight coefficient for each environmental factor. Finally, the comprehensive weight coefficient of each index is merged into a weight set ω.

(5) Fuzzy comprehensive evaluation. The comprehensive weight set ω calculated by entropy weight method and improved analytic hierarchy process is fuzzy synthesized with membership degree evaluation matrix H. By using a weighted linear transformation method, the fuzzy comprehensive evaluation result of the pig house environment is ultimately obtained.

$$Y = \omega \bullet H = \{y_1, y_2, y_3\} \tag{7}$$

where: Y is the comprehensive evaluation result matrix.

Consequently, the evaluation result matrix corresponding to the three suitability conditions of the pig house environment is obtained, and the suitability status of the pig house environment is determined based on the maximum membership principle.

Selection of membership function types

The key to evaluating the suitability of the pig house environment lies in determining the membership functions for the pig house environment. Based on the nature of the pig house environment evaluation factors, the functional relationship between membership degree and indicators needs to be constructed using continuous functions. In the evaluation of pig house environmental suitability, commonly used types of membership functions include ridge-shaped membership function, trapezoidal membership function, and triangular membership function. The ridge-shaped membership function optimizes the edges and corners of the trapezoidal membership function, which can reduce errors when calculating high membership degrees. Compared to the triangular membership function, the ridge-shaped membership function has better distinction between levels. Therefore, this paper uses the ridge-shaped membership function to calculate the membership degree matrix of evaluation factors such as temperature and humidity in the pig house environment. The expressions of the ridge-shaped membership function are shown in Formulas (8)-(10).

$$\text{Lower Type: } u(x) = \begin{cases} 1 & x \le a \\ \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{b-a}(x - \frac{b+a}{2}) & a < x < b \\ 0 & x \ge b \end{cases} \tag{8}$$

$$\text{Middle Type: } u(x) = \begin{cases} 0 & x \le a \\ \frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{b-a}(x - \frac{b+a}{2}) & a < x < b \\ 1 & b \le x \le c \\ \frac{1}{2} - \frac{1}{2}\sin\frac{\pi}{d-c}(x - \frac{d+c}{2}) & c < x < d \\ 0 & x \ge d \end{cases} \tag{9}$$

$$\text{Upper Type: } u(x) = \begin{cases} 0 & x \le a \\ \frac{1}{2} + \frac{1}{2}\sin\frac{\pi}{b-a}(x - \frac{b+a}{2}) & a < x < b \\ 1 & x \ge b \end{cases} \tag{10}$$

where: x represent the index values of the evaluation factors u_i, with its interval endpoints denoted as x_i 、 x_{i+1}. The membership degree of each evaluation level in the set of evaluation results is denoted as $u(x)$. The a, b, c, and d respectively represent the demarcation points in the set of evaluation results corresponding to various environmental factors in the pig house environment evaluation system. Each index value in the set of evaluation factors has a corresponding fuzzy logical relationship. The ridge-shaped distribution membership functions of various environmental factors, established based on the pig house environment evaluation index system, are shown in Figure 5.

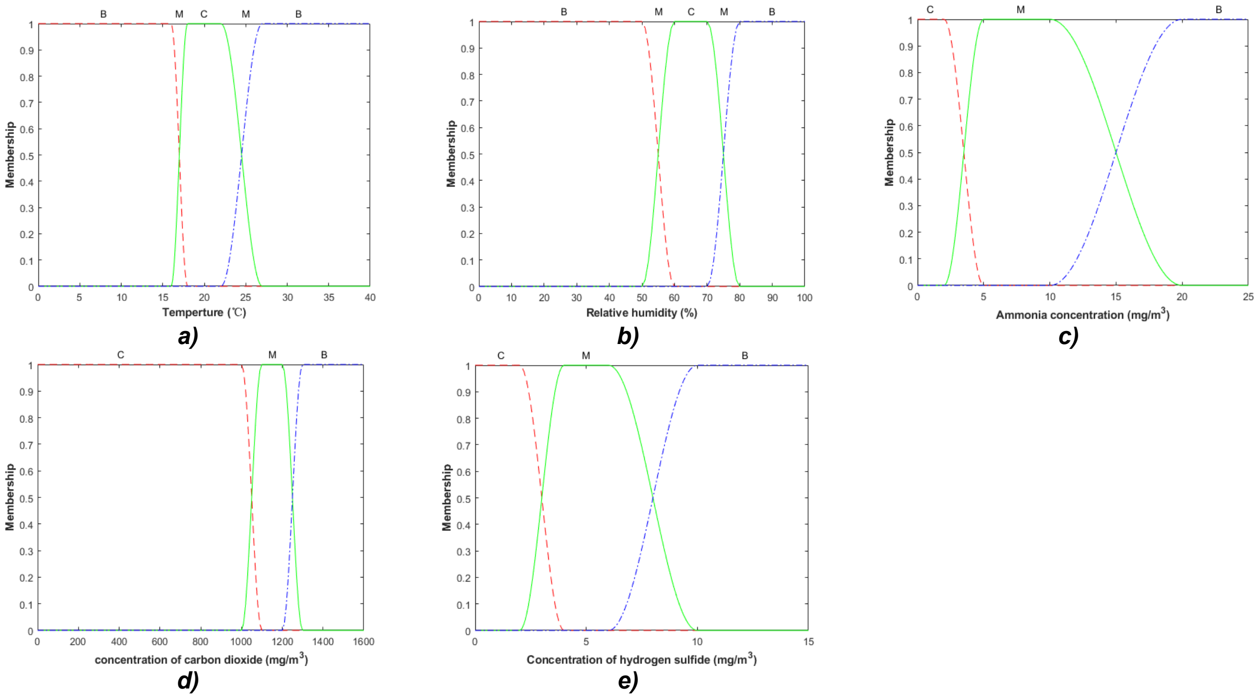

Fig. 5 – Membership function curves of each environmental factor

a) Temperature; b) Relative humidity; c) Ammonia concentration;
d) Concentration of Carbon dioxide; e) Concentration of hydrogen sulfide

In Figure a), b), c), d) and e), the three curves from left to right are the ring down type, the middle type and the ring up type.

Method for determining weight

(1) Weight calculation method based on the entropy weight method

Unlike the improved Analytic Hierarchy Process, which typically emphasizes subjective factors, the entropy weight method is a method of empowerment that objectively determines weight through observed values. The smaller the entropy value, the more disordered the information is, and thus its value in comprehensive evaluation is higher, resulting in a larger corresponding weight. For example, when there is a significant sudden increase in the temperature of the pig house, this algorithm will increase the weight of the temperature factor while reducing the weights of other factors with smaller changes. The algorithm process is as follows.

1) Standardize the data based on the following formula:

$$X_{ij}^{'} = \frac{X_{ij} - \min(X_{1j}, X_{2j}, \cdots, X_{nj})}{\max(X_{1j}, X_{2j}, \cdots, X_{nj}) - \min(X_{1j}, X_{2j}, \cdots, X_{nj})} + 1 \qquad j = 1, 2, 3, \cdots, m \tag{11}$$

2) Calculate the weight of the environmental parameter data for the j th item after standardization based on the following formula:

$$p_{ij} = \frac{X_{ij}^{'}}{\sum_{i=1}^{n} X_{ij}^{'}} \qquad j = 1, 2, 3, \cdots, m \tag{12}$$

3) Calculate the information entropy value of the environmental parameter for the j th item based on the following formula:

$$k = \frac{1}{\ln(n)} \tag{13}$$

$$e_j = -k \sum_{i=1}^{n} p_{ij} \ln(p_{ij}) \tag{14}$$

4) Calculate the information entropy redundancy of each environmental factor in the pig house based on the following formula:

$$f_j = 1 - e_j \tag{15}$$

5) Calculate the weight of each environmental parameter:

$$W_j^R = \frac{f_j}{\sum_{j=1}^{m} f_j} \qquad j = 1,2,3,\cdots,m \tag{16}$$

(2) Weight calculation method based on the improved analytic hierarchy process

Based on relevant research findings and the experience of livestock experts, the importances of evaluation indicators for multiple environmental factors in the pig house are determined as follows: environmental temperature, relative humidity, ammonia gas concentration, carbon dioxide concentration, and hydrogen sulfide concentration. The 1-9 scales method is used to compare these evaluation indicators with each other and construct a comparison matrix. The specific descriptions of the 1-9 scales method are shown in the table 2 below:

Table 2

Description of 1-9 scales

Relative importance level	Scale significance
1	Equal importance
3	Slight importance
5	Obvious importance
7	Strong importance
9	Absolute importance
2, 4, 6, 8	The middle level of two adjacent levels

By conducting pairwise comparisons of environmental temperature (T), relative humidity (O), ammonia gas concentration (N), carbon dioxide concentration (E), and hydrogen sulfide concentration (HS), the importance of each factor is determined, resulting in a comparison matrix L. Then, the importance ranking index v_i for each factor is calculated, which are represented by the sum of each row in the comparison matrix L.

$$L = \begin{array}{c} \\ T \\ O \\ N \\ E \\ HS \end{array} \begin{array}{c} \begin{array}{ccccc} T & O & N & E & HS \end{array} \\ \begin{bmatrix} 1 & 2 & 3 & 4 & 3 \\ 1/2 & 1 & 2 & 3 & 2 \\ 1/3 & 1/2 & 1 & 3 & 2 \\ 1/4 & 1/3 & 1/3 & 1 & 1/3 \\ 1/3 & 1/2 & 1/2 & 3 & 1 \end{bmatrix} \end{array} \qquad i = 1,2,3,4,5 \tag{17}$$

where:

v_i is the importance ranking index for each factor indicator, and l_{ij} is the element in the i th row and j th column of the comparison matrix L.

Construct an indirect judgment matrix K reflecting the relative importance of each environmental factor. Let

$$q_m = \frac{v_{\max}}{v_{\min}} \tag{18}$$

where:

$v_{\max}$ is the maximum ranking index, $v_{\min}$ is the minimum ranking index, and q_m is the base point comparison scale. The indirect judgment matrix K is:

$$K = (k_{ij})_{5\times5} = \begin{cases} \dfrac{v_i - v_j}{v_{\max} - v_{\min}}(q_m - 1) + 1 & v_i - v_j \ge 0 \\ 1 / \left[\dfrac{v_i - v_j}{v_{\max} - v_{\min}}(q_m - 1) + 1 \right] & v_i - v_j < 0 \end{cases} \qquad (i = 1,2,3,4,5)\ (j = 1,2,3,4,5) \tag{19}$$

Transform the indirect judgment matrix K into an antisymmetric matrix S and then construct a quasi-optimal consistent matrix Z, the consistency requirement can be satisfied.

$$s_{ij} = \lg(k_{ij}) \qquad (i=1,2,3,4,5)\ (j=1,2,3,4,5) \tag{20}$$

where:

S is the antisymmetric matrix; s_{ij} is the element in the i th row and j th column of the antisymmetric matrix S; k_{ij} is the element in the i th row and j th column of the indirect judgment matrix K.

$$z_{ij} = 10^{\frac{1}{n}\sum_{k=1}^{n}(s_{ik}-s_{jk})} \qquad (i=1,2,3,4,5)\ (j=1,2,3,4,5) \tag{21}$$

where:

z_{ij} is the element in the i th row and j th column of the quasi-optimal consistent matrix Z; s_{ik} is the element in the i th row and k th column of the antisymmetric matrix S; s_{jk} is the element in the j th row and k th column of the antisymmetric matrix S.

Finally, calculate the largest eigenvalue and the corresponding eigenvector of the quasi-optimal matrix Z, and normalize them as shown in equations (22) and (23) to obtain the required weight for each factor.

$$ZW = \lambda_{\max} W \tag{22}$$

$$W_j^A = \frac{W_j}{\sum_{j=1}^{5} W_j} \tag{23}$$

where: $\lambda_{\max}$ is the maximum eigenvalue of Z, and W is the relative weight vector.

After the aforementioned steps of the improved Analytic Hierarchy Process, the subjective weight of the evaluation index for each environmental factor is calculated, as shown in the table 3.

Table 3

Evaluation indicator weights of pig house environment

Evaluation index	Weight
Temperature	0.4784
Relative humidity	0.2153
Ammonia gas	0.1468
Carbon dioxide	0.0562
Hydrothion	0.1033

(3) Combined weight calculation

Combine the subjective and objective weight values to obtain the combined weights. This calculation method can, to a certain extent, reduce the deviation of subjective weights and the one-sidedness of objective weights while leveraging their respective advantages, making the weight calculation more scientific. The comprehensive weights of the indices are calculated using the following formula:

$$\omega_j = \frac{W_j^A W_j^R}{\sum_{j=1}^{n} W_j^A W_j^R} \tag{24}$$

where:

ω_j is the comprehensive weight; W_j^A is the subjective weight calculated using the improved Analytic Hierarchy Process; W_j^R is the objective weight calculated using the entropy weight method. The comprehensive weights of the evaluation indicators are combined into a weight set ω, and ω satisfy $\omega = [\omega_T\ \omega_O\ \omega_N\ \omega_E\ \omega_{HS}]$.

RESULTS AND ANALYSIS

System data fusion effect test

Taking temperature as an example, the pig house temperature value measured by the precision temperature measuring instrument is used as the standard temperature.

During testing, each group of sensor node from 20 monitoring points in the pig house collected temperature data 10 times. The collected data from the sensor nodes are optimized using a median filtering function to reduce the influence of random factors. Subsequently, using MATLAB (2020a), the temperature data optimized by the median filtering function was compared with the temperature data processed by the algorithm discussed in this paper (a data fusion algorithm based on the median filtering function and Kalman filtering) and the standard temperature of 25.4 °C collected by a precision temperature instrument. The results are shown in Figure 6.

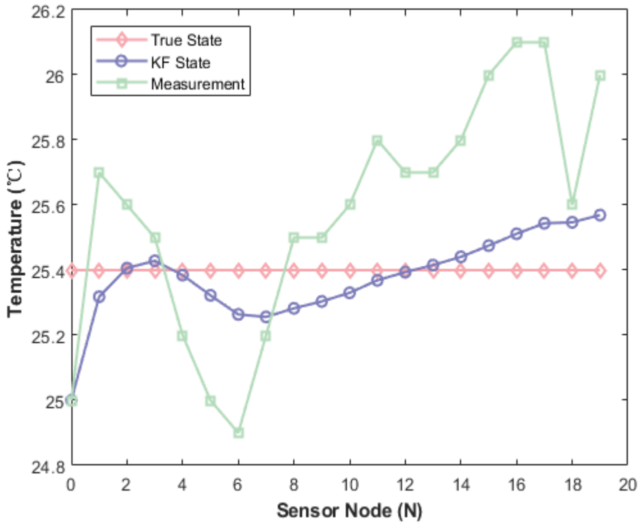

Fig. 6 – Comparison picture of the temperature values measured by three temperature measurement methods

From Figure 6, it can be seen that the average temperature measured by the 20 groups of sensor nodes is 25.57°C, while the average temperature after optimization by the fusion algorithm in this paper is 25.37°C, which is closer to the standard temperature of 25.4°C measured by the precision temperature instrument and the temperature data curve is smoother compared to that measured by the sensor nodes.

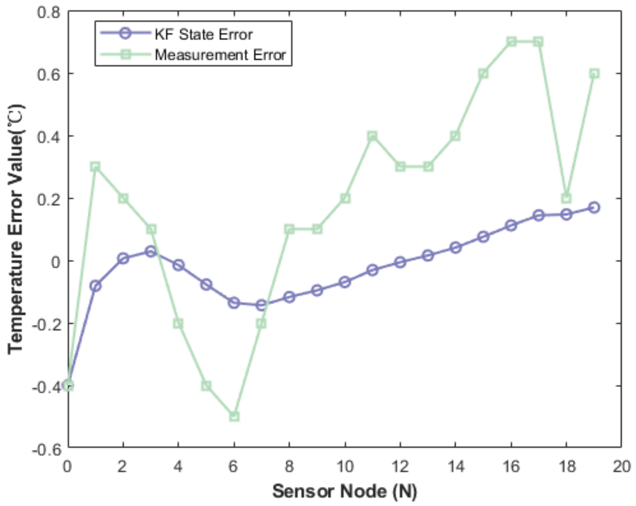

Fig. 7 – Error comparison results

From the error results comparison figure (Figure 7), it is evident that the measurement value error from the sensor nodes is 0.67% and the error range between -0.5°C and 0.7°C, indicating significant fluctuations. In contrast, the error value after applying the algorithm proposed in this paper is 0.12% and the error range is concentrated between -0.1°C and 0.2°C. The error comparison results demonstrate that the Kalman filtering data fusion algorithm proposed in this paper effectively improves the accuracy of sensor measurement data, indicating that the Kalman filtering algorithm meets the data processing requirements of this paper.

System operation test

The sensor nodes for collecting environmental information in the pig house are powered by an independent power source and use Wi-Fi for data transmission. Figure 8 show the historical data curves of pig house environment detection recorded every minute.

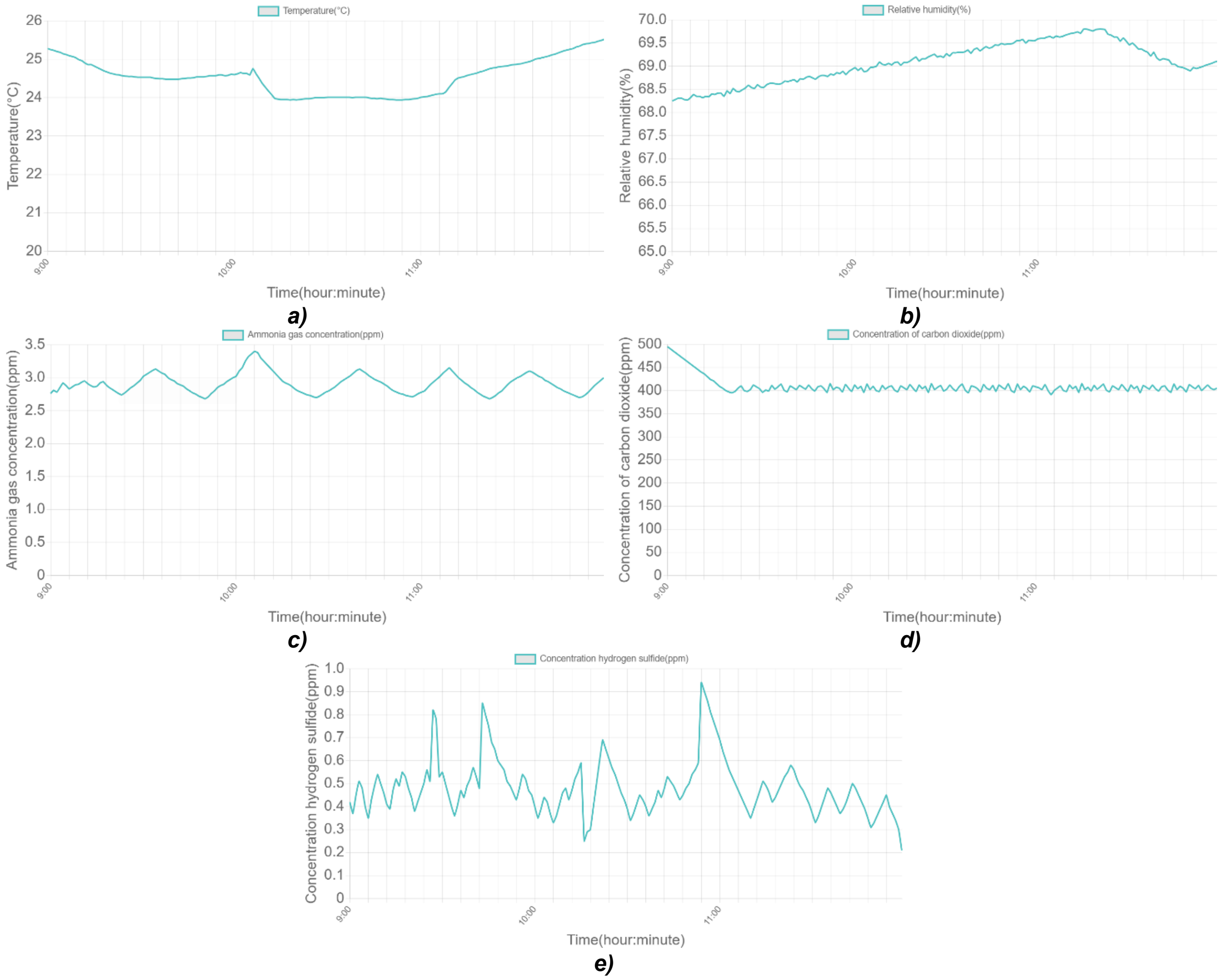

Fig. 8 – Historical data curves of environmental monitoring

a) Temperature; b) Relative humidity; c) Ammonia concentration;
d) Concentration of Carbon dioxide; e) Concentration of hydrogen sulfide

Environmental evaluation test

According to the collected 24h environmental factor data of pig house on October 11, 2024, the median filter function and Kalman filter data fusion algorithm were used to process these environmental data, and combined with fuzzy comprehensive evaluation, the membership curves of pig house environmental suitability evaluation at each time were obtained, as shown in Figure 9.

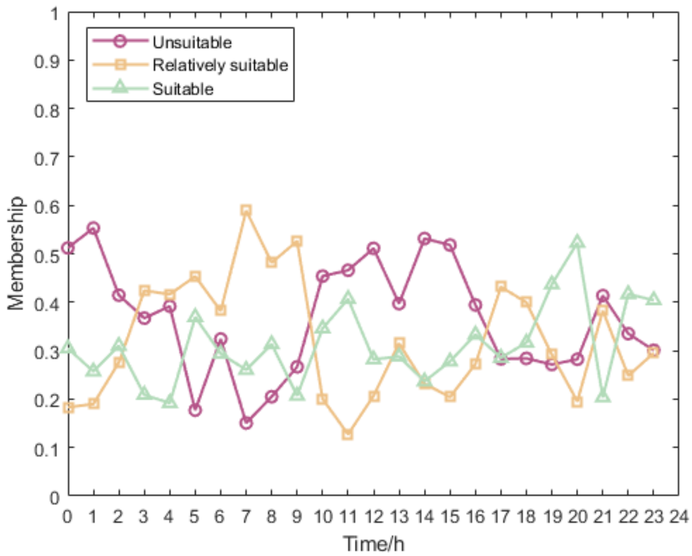

Fig. 9 – Membership degree curves of environmental suitability evaluation of pig house

From Figure 9, it can be seen that on this day, the combined proportion of suitable and relatively suitable conditions in the pig house environment is much greater than that of unsuitable conditions. The condition of the pig house environment is determined by multiple environmental factors and taking the data at 10:00 AM on a particular day as an example, the results after processing with the Kalman filter are as follows: temperature is 24.2°C, relative humidity is 66.82%, ammonia gas concentration is 5.3 ppm, carbon dioxide concentration is 1243 ppm, and hydrogen sulfide concentration is 0.05 ppm. By inputting these environmental factor data into the ridge-shape membership function, the membership matrix is obtained as shown in Eq. (25).

$$H=\begin{bmatrix} 0 & 0.59 & 0.41 \\ 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & 0.61 & 0.39 \\ 1 & 0 & 0 \end{bmatrix} \tag{25}$$

Through the comprehensive weight calculation method, the weight set at this time is derived as $\omega=[0.4625, 0.2109, 0.1466, 0.0551, 0.1249]$. Combined with Equation (15), a fuzzy comprehensive evaluation of the suitability of the pig house environment is conducted, resulting in evaluation outcome $Y=[0.1249, 0.6640, 0.2111]$, which corresponds to respectively the evaluation result set D = {suitable, relatively suitable, unsuitable}. According to the principle of maximum membership, at this time, the proportion of "suitable" in the evaluation result set is 0.1249, "relatively suitable" has the highest proportion at 0.6640, and "unsuitable" is 0.2111. Therefore, it is determined that the pig house environment at this time is "relatively suitable." The evaluation results of the pig house environment can be displayed on the remote monitoring page, as shown in Figure 10 and Figure 11. The system client can display the environmental information of the current measurement area and provide the current environmental suitability status. The visual interface of the cloud platform is consistent with the data display results of the WeChat mini program, which proves that the performance of each unit of the system is stable, the operation is normal, and the design objectives are met.

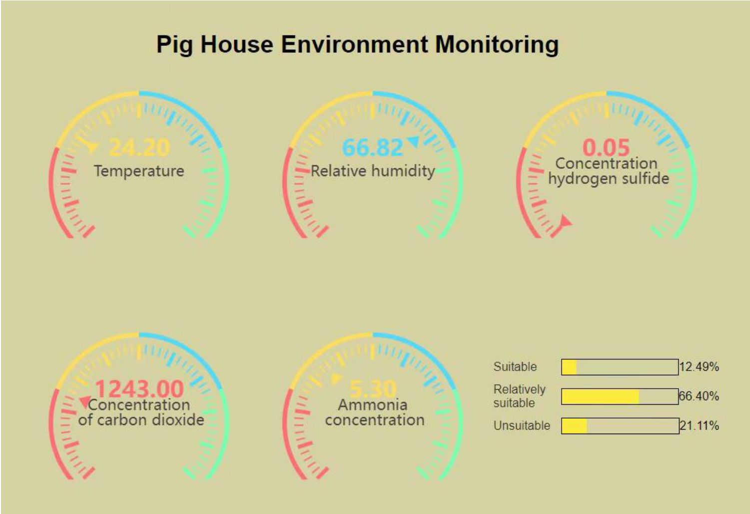

Fig. 10 – Cloud platform interface

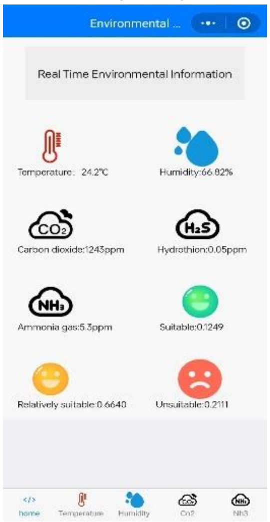

Fig. 11 – WeChat mini program page

CONCLUSIONS

This paper designs a pig house environmental monitoring system based on Internet of Things technology, which can monitor the environmental data in the pig house in real time. The Kalman filter data fusion algorithm is adopted in the system to ensure the accuracy of monitoring data, and this data fusion algorithm is implemented in the main control chip of the sink node. The test results of temperature data show that the error of Kalman filter algorithm is only 0.12%, which meets the monitoring accuracy requirement. In order to achieve an accurate evaluation of the pig house environment, a fuzzy comprehensive evaluation system for pig house is constructed, avoiding the one-sidedness of single environmental factor evaluation methods. The system combines subjective and objective weight calculation methods, reducing the deviation of subjective weights and the one-sidedness of objective weights to a certain extent, making the weight calculation more scientific. The field tests indicate that the system operates stably, and the cloud platform can display real-time environmental data and suitability evaluation results of pig houses, meeting the system requirements.

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