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# Design of a Closed Piggery Environmental Monitoring and Control System Based on a Track Inspection Robot

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**Abstract:** To improve environmental quality in enclosed piggeries, a monitoring and control system was designed based on a track inspection robot. The system includes a track mobile monitoring platform, an environmental control system, and a monitor terminal. The track mobile monitoring platform consists of three main components: a single-track motion device, a main box containing electronic components, and an environmental sampling device. It is capable of detecting various environmental parameters such as temperature, humidity, $NH_3$ concentration, $CO_2$ concentration, light intensity, $H_2S$ concentration, dust concentration, and wind speed at different heights below the track. Additionally, it can control on-site environmental control equipment such as lighting systems, ventilation systems, temperature control systems, and manure cleaning systems. The networked terminal devices enable real-time monitoring of field equipment operating status. An adaptive fuzzy PID control algorithm is embedded in the system to regulate the temperature of the piggery. Field tests conducted on a closed nursery piggery revealed that the system effectively controlled the maximum temperature range within 2 °C. The concentrations of $CO_2$, $NH_3$, and PM2.5 were maintained at a maximum of 1092 mg·m$^{-3}$, 16.8 mg·m$^{-3}$, and 35 µg·m$^{-3}$, respectively. The light intensity ranged from 51 to 57 Lux, while the wind speed remained stable at approximately 0.35 m·s$^{-1}$. The $H_2S$ concentration was significantly lower than the standard value, and the lowest relative humidity recorded was 18% RH at high temperatures. Regular humidification is required in closed piggeries and other breeding places when the system does not trigger the wet curtain humidification and cooling function, as the relative humidity is lower than the standard value. By controlling the temperature, the system combined with a humidification device can meet environmental requirements. The control method is simple and effective, with a wide range of applications, and holds great potential in the field of agricultural environmental control.

**Keywords:** enclosed piggery; monitoring and control; track inspection robot; fuzzy PID

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## 1. Introduction

China, as the world's largest consumer of pork, accounts for over 60% of the world's total meat consumption [1]. Unfortunately, intensive and large-scale swine production has led to an increase in pig mortality and a decline in pork quality due to excessive breeding density. An effective solution to this problem is to improve the quality of the piggery environment [2,3].

In recent years, significant progress has been made by scholars in developing environmental monitoring systems for swine production. Huang, J.S. et al. [4] have designed a piggery environment control system that utilizes an STM32 single-chip microcomputer as the control core. This system is designed to regulate environmental factors such as temperature and humidity from fixed monitoring positions, resulting in better monitoring and control of the environment. Liu, Y.C. et al. [5] developed a wheeled mobile terminal environmental monitoring robot for piggeries. This robot enables three-dimensional monitoring of environmental status and addresses the labor-intensive issues of manual sampling and patrol inspection. Additionally, Wu, Z.D. et al. [6] designed a stable and reliable wireless monitoring system for piggeries using LoRa wireless communication technology. The system's terminal nodes and main control nodes were built with a star topology. Zhu, Y. et al. [7] utilized ZigBee wireless communication technology for transmitting data collected by sensors. Additionally, PLC controllers were employed to manage field devices such as cooling fans and circulation fans. This approach effectively addresses the challenges associated with complex wiring and the high failure rate often encountered in traditional wiring methods. Madona, E. et al. [8,9] developed a temperature monitoring system that offers low reading errors and enables fast remote communication through the use of LoRa technology. To address the challenge of transmitting large amounts of monitoring data from multiple points in a piggery, many scholars have utilized wireless communication technologies such as ZigBee, WIFI, and LoRa to establish a multi-hop self-organizing network for continuous monitoring of environmental parameters [10–15]. The principle of the environmental monitoring system in livestock houses, such as cowsheds and chicken sheds, is similar to that of piggeries. Most of these systems use fixed monitoring methods. The main difference lies in the specific monitoring sites and environmental control standards [16–20]. The working principle of an environmental monitoring system that is applicable to livestock houses can also be applied to greenhouses and other similar scenarios involving plant growth [21–24].

In summary, environmental control systems that use fixed multi-position and multi-sensor measurements have limitations such as low sensor utilization and difficult wiring. Additionally, fixed-point monitoring methods cannot effectively monitor air quality at varying heights. In order to solve these problems, a comprehensive environmental monitoring system is developed using a track inspection robot as a mobile monitoring platform. This system consists of a track inspection robot, an environmental conditioning system, and a remote terminal. It is capable of monitoring the environmental quality in livestock sheds or greenhouses at different heights and making intelligent adjustments to enhance the environmental conditions. The system has a wide range of applications, bringing greater economic benefits to enterprises, and showing promising development prospects.

## 2. Materials and Methods

### *2.1. Piggery Structure*

This system was designed for a nursery piggery owned by Juhenongmu Co., Ltd., located in Hebi City, Henan Province, China. The piggery's structural layout is illustrated in Figure 1, with dimensions of 10 m in span, 2.5 m in height, and 40 m in length. The piggery features a double-row layout with a 1 m wide aisle in the middle, two wet curtains at the front, and six fans of different specifications on the rear wall. The T-shaped track of the track inspection robot is arranged above the pig's activity area, showing a U-shaped plane layout based on the construction pattern of the piggery fence. The ground area is mainly divided into the manure cleaning area (concrete-slatted floor) and the floor heating area. The monitoring points are set 15 m away from the back wall, as shown in Figure 1.

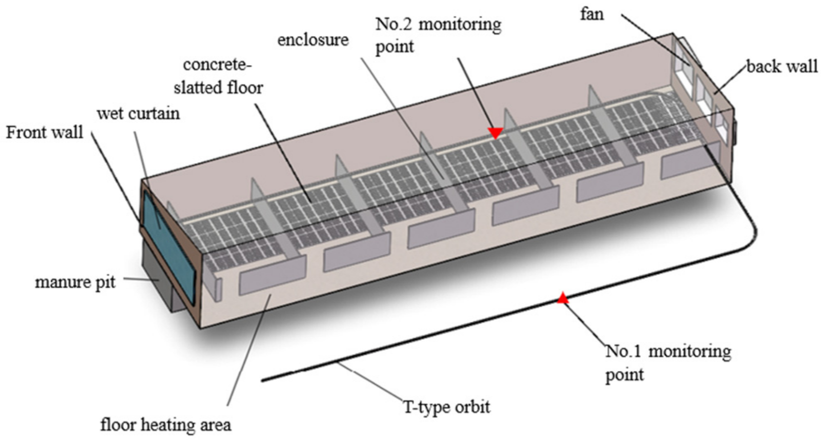



**Figure 1.** The piggery model diagram (single row).

*2.2. Working Principle*

The piggery environmental monitoring system (Figure 2) consists of a track inspection robot and a monitoring terminal. It is connected to environmental control equipment to create an adaptive environmental system. The system's primary functions are to monitor environmental parameters, issue alerts for environmental abnormalities, enable remote monitoring, and adjust the piggery's environment adaptively.

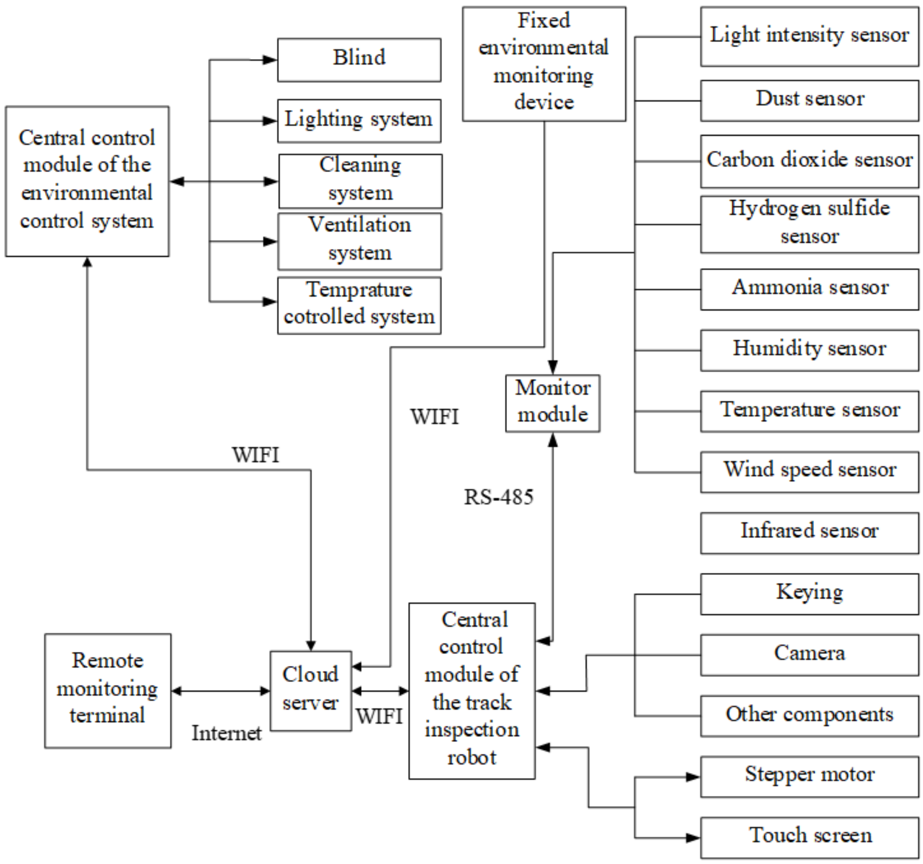



**Figure 2.** The hardware structure of the piggery environmental monitoring system.

The track inspection robot has two working modes: manual and automatic. In manual mode, management personnel can control the robot's motion direction and monitoring sites through the monitoring terminal. The primary working mode is automatic, as shown in Figure 3. In this mode, infrared sensors located at the front and rear of the robot upload information about detected markers on the track to the central control module. The module then determines the robot's movement direction on the track using an internal program. During the movement of the track inspection robot, its No. 1 infrared sensor detects the region recognition set on the T-type track and stops the movement to record the position information of the corresponding monitoring point. The telescopic mechanism at the bottom of the main box is then used to detect the environmental parameters at different height positions of the preset monitoring sites. The collected environmental data information is uploaded to the cloud server and compared with the parameter values pre-set by the production manager. If the detection parameter value falls within the set range, the control system does not respond. In contrary, the system sends a relevant alarm to the production manager through the monitor terminal, and the control system will send corresponding control instructions to the on-site control equipment and adjusts the operation of the equipment (floor heating, wet curtain, and fans, etc.) in time, so as to realize the adaptive regulation of the piggery environment.

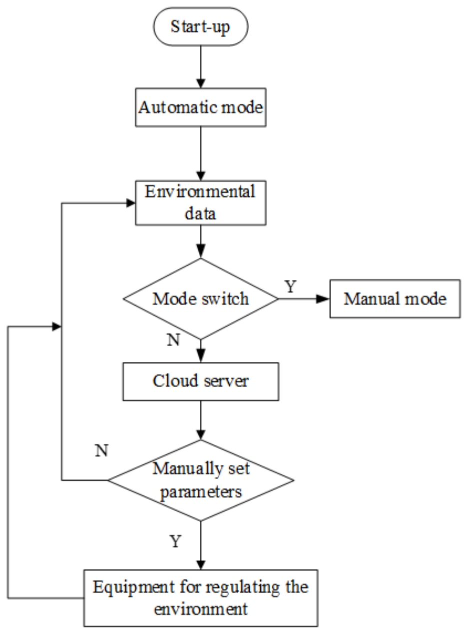



**Figure 3.** Working principle of automatic mode.

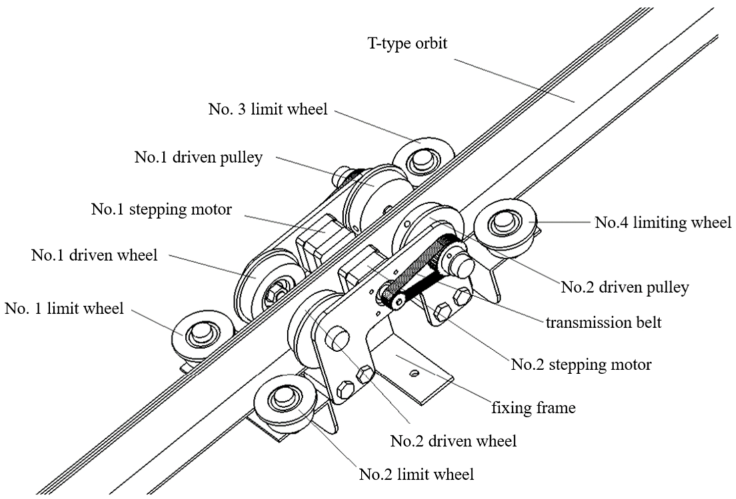
In the control system, the main data acquisition device is situated at the base of the track inspection robot, providing coverage of all areas directly beneath the track. Additionally, secondary data acquisition devices are fixed installations responsible for monitoring specific locations, such as septic tanks, to prevent the accumulation of harmful gases. The collaboration between the master–slave device can provide a comprehensive display of the environmental conditions in the piggery, thereby reducing the likelihood of monitoring errors and system false alarms. The environmental monitoring module of the robot collects data, which is then transmitted to the central control module through the RS-485 interface and uploaded to the cloud server via the WIFI module. The cloud server communicates with the track inspection robot using a two-way TCP protocol and is responsible for receiving, processing, and storing data, ensuring data security. The terminal application layer facilitates two-way communication with the cloud server, allowing for real-time viewing of environmental data and historical records, as well as remote control of the operation status of the field devices in the piggery. The piggery environment adjustment equipment communicates with the cloud server via WIFI.

The environmental control system is capable of receiving instructions via a wireless module to regulate the temperature control, ventilation, lighting, and cleaning systems in order to achieve optimal environmental conditions. The temperature control system, which is responsible for adjusting temperature and humidity in the house, includes a heating plant, wet curtains, and fans. The ventilation system in piggery refers to the use of fans to eliminate harmful gases and maintain air quality. The lighting system provides the necessary light intensity to meet the growing needs of pigs. The manure cleaning system involves the use of a cleaning device located under the concrete-slatted floor to remove manure and food residues in a timely manner, thus preventing the generation of harmful gases.

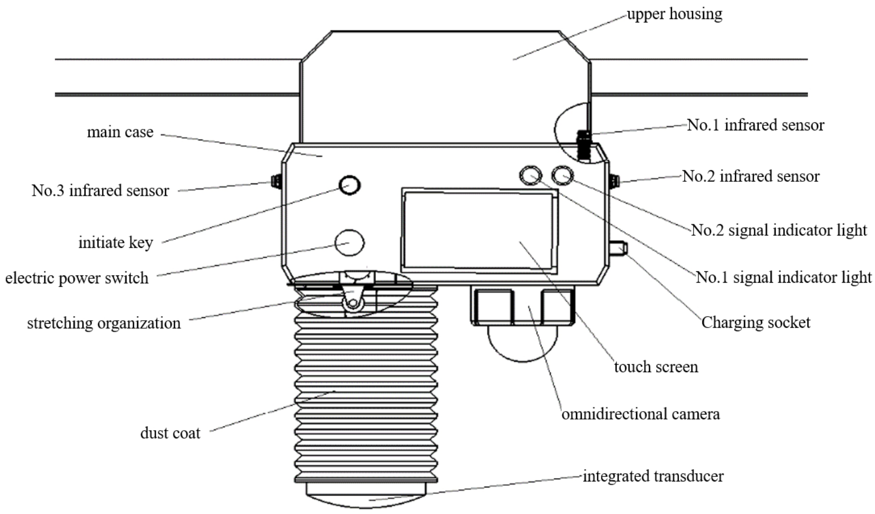
### 2.3. System Hardware Design

#### 2.3.1. Travel Mobile Monitoring Platform

The mobile monitoring platform (Figure 4) consists of three main components: the travel mechanism (Figure 4a), the lifting monitoring mechanism, and the main box. To ensure that the equipment is well-balanced and stable, the travel mechanism is designed symmetrically. The stepper motors located on both sides of the travel mechanism provide power to the driven pulley through synchronous belts. The driven pulleys on both sides, along with the driven wheel, work together to maintain balance in the front/back and left/right directions. The traveling mechanism of the mobile monitoring platform is equipped with four limiting wheels that serve the purpose of guiding the movement of the vehicle, thereby enhancing its stability while turning and driving straight. Additionally, the telescoping mechanism located at the bottom of the rear end of the main chassis is fitted with an integrated transducer (Figure 4b) that can effectively monitor various environmental factors.




(**a**)




(**b**)

**Figure 4.** Track mobile monitoring platform. (**a**) Travel mechanism; (**b**) Mobile monitoring platform structure diagram.

The telescopic drive mechanism enables multi-type and layered air quality monitoring in a piggery. Once the equipment reaches the designated monitoring position, the central control module of the track inspection robot instructs the travel mechanism to brake. The telescopic drive mechanism controls the wire rope to adjust the height of the integrated sensor, allowing for a lifting range of 0~1.5 m. The main box features a sealed structure design to protect electronic components, including the main control board and power supply, from erosion. Additionally, a dust coat cover is installed outside the lifting mechanism to safeguard the internal mechanical structure and circuit from erosion caused by highly corrosive gases present in the piggery. The monitoring module is equipped with a separated design of circuit boards and sensors to prevent excessive contact between circuit boards and corrosive air, thus prolonging its service life.

### 2.3.2. Central Control Module

The track inspection robot is equipped with the ATMEGA 2560-16AU processor developed by ATMEL, which serves as the control core. This processor is an 8-bit microcontroller with AVR-enhanced RISC architecture and low power consumption. It has numerous analog and digital pins and a fast processing speed, with a data throughput of 1 MIPS·MHZ$^{-1}$ in a single clock cycle [25]. The central control module is responsible for three main functions: receiving and processing sensor data, executing motion programs, and communicating with the server through the wireless module.

### 2.3.3. Monitor Module

The monitoring module for the piggery includes sensors, a PCB circuit board, and accessory components (Figure 5). It uses an RS-485 [26] interface to communicate with the central control module (U1) and is responsible for collecting data on temperature, humidity, $NH_3$ concentration, $H_2S$ concentration, $CO_2$ concentration, light intensity, PM2.5 concentration, and wind speed. Additionally, a secondary acquisition device, which can be a single or multiple sensor module with a wireless transmission function, is responsible for monitoring special positions that are difficult to monitor using the septic tank or track inspection robot. In this project, a PM2.5 sensor is used instead of a dust sensor, and the relevant sensor selections and parameters are shown in Table 1.

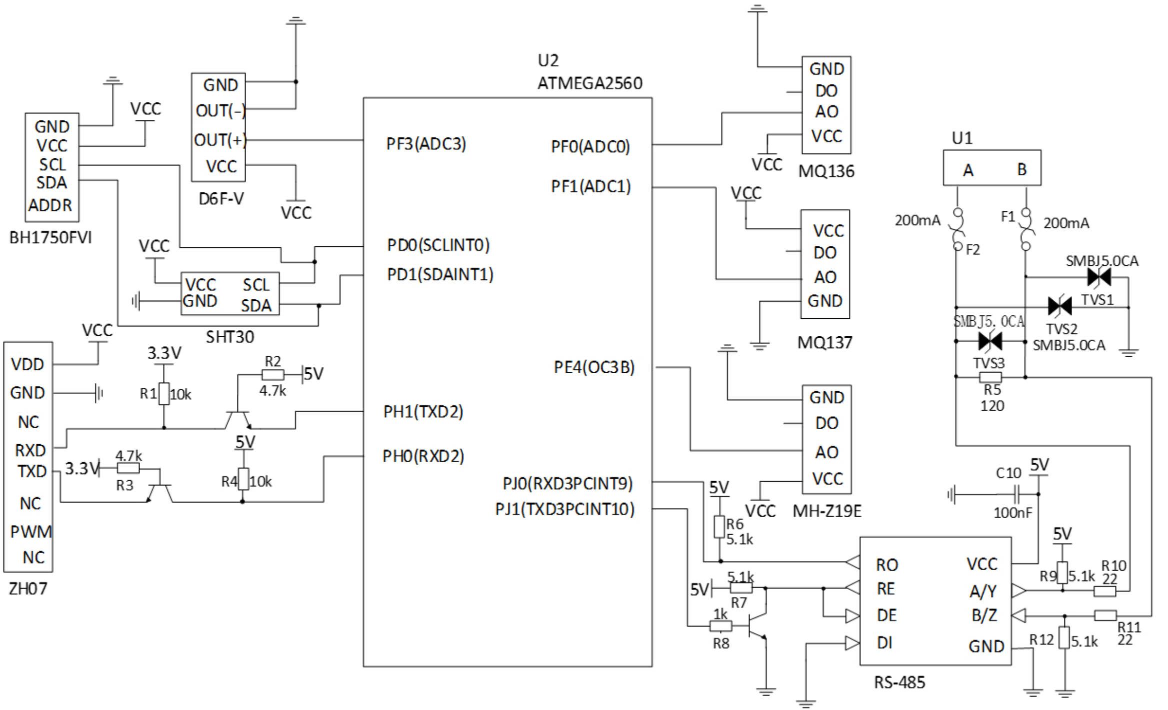



**Figure 5.** Hardware circuit of main monitoring module.

**Table 1.** Sensor selections and parameters.

| The Label of the Sensor | Type [1] | Detection Factor | Detection Range (ppm) | Response Time (s) | Communication Protocol |
|---|---|---|---|---|---|
| MQ137 [27] | semi-conductor transducer | $NH_3$ | 5~500 ppm | $\leq 5$ | analog quantity |
| MQ136 [28] | | $H_2S$ | 1~200 ppm | | |
| MH-Z19E | infrared sensor | $CO_2$ | 400~2000 ppm | $\leq 3$ | PWM |
| SHT30 [29] | thermocouple transducer | temperature | −40~+80 °C | $\leq 2$ | $I^2C$ |
| | | humidity | 0~100% RH | $\leq 8$ | |
| ZH07 | infrared sensor | PM2.5 | 0~1000 $\mu g \cdot m^{-3}$ | <30 | uart |
| BH1750FVI | semi-conductor transducer | intensity of illumination | 0~65,535 Lux | | $I^2C$ |
| D6F-V03A1 | thermal mass flow sensor | wind velocity | 0~3 $m \cdot s^{-1}$ | | analog quantity |

[1] Sensor types are classified according to working principles. All sensors purchased through the market were fully checked at the factory.

### 2.3.4. WIFI Module

The piggery is a large and complex environment that requires a wireless communication method with strong versatility, long transmission distance, and a high communication rate. After considering various wireless transmission technologies and project needs, WIFI communication technology was selected. The ESP-07S chip with a working voltage of 3.3 V was chosen as the WIFI communication module [30]. It communicates with the central control module (U1) through the serial port to provide networking functions (Figure 6). The chip is small, stable, does not consume much power, supports transparent transmission, and is reasonably priced.

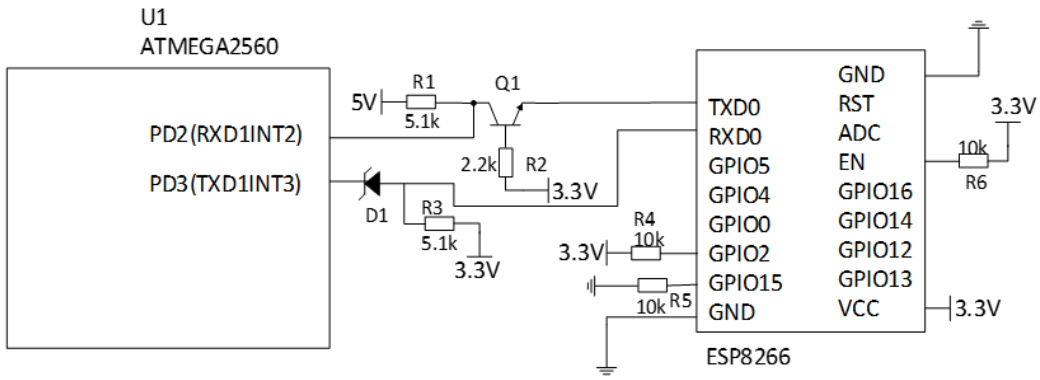



**Figure 6.** Communication circuit of WIFI module.

### 2.3.5. Human–Computer Interaction (HCI) Module

The HCI module is a touchable LCD screen that is installed on the side of the track inspection robot, as shown in Figure 4b. Its control principle is demonstrated in Figure 7, and it communicates with the central control module via the serial port. The main functions of the HCI module include the real-time display of environmental monitoring data, WIFI networking prompt, running status prompt, equipment alarm prompt, start-up and manual mode switching, historical environmental data query, and system settings. Breeding management personnel can use the interface to observe changes in environmental parameters in the piggery or perform operations such as changin system settings.

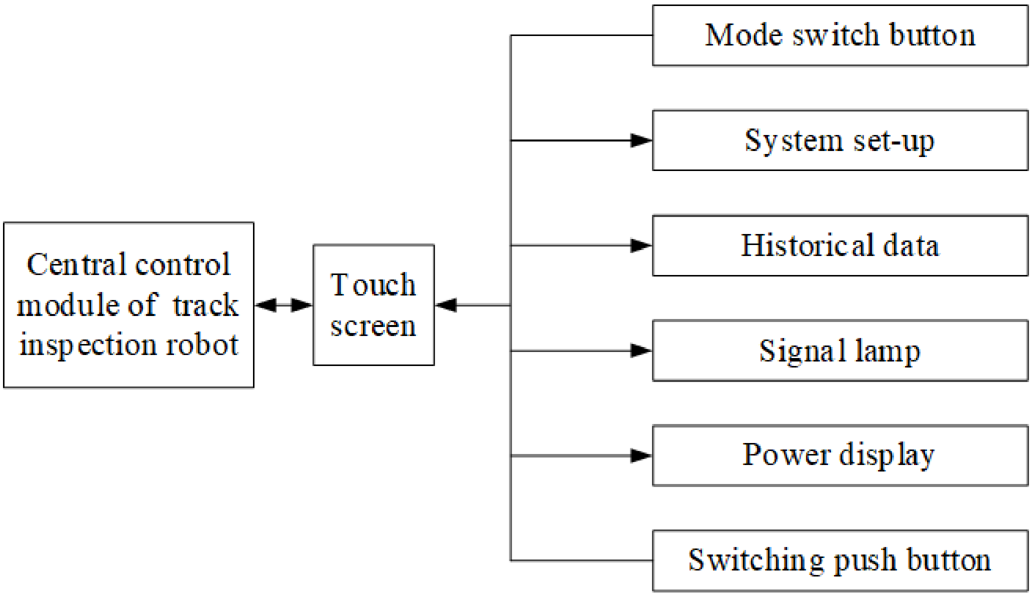



**Figure 7.** The logical design of the human–computer interaction module.

### *2.4. Remote Monitoring Terminal Design*

Remote monitoring is facilitated through the OneNET cloud platform and is visualized via networked electronic equipment (Figure 8). This system allows for convenient and efficient management of sensor data and equipment operation status. The sensor data is presented in a line chart format, depicting changes over time, and also supports data downloading.

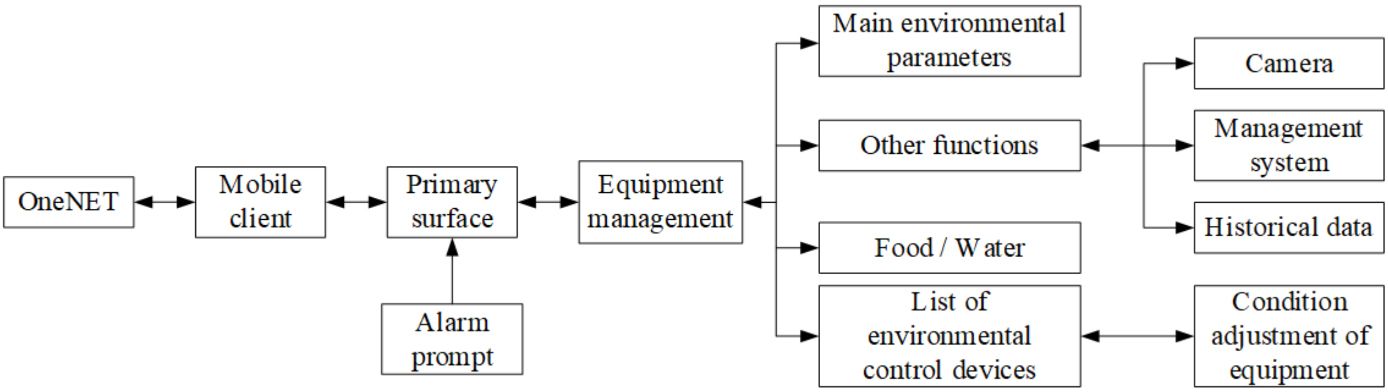



**Figure 8.** Remote monitoring terminal logic structure (WeChat applet).

### *2.5. Motion Program Design of Track Inspection Robot*

#### 2.5.1. Main Program Design

The track inspection robot operates in two modes: network and no network. The workflow is illustrated in Figure 9.

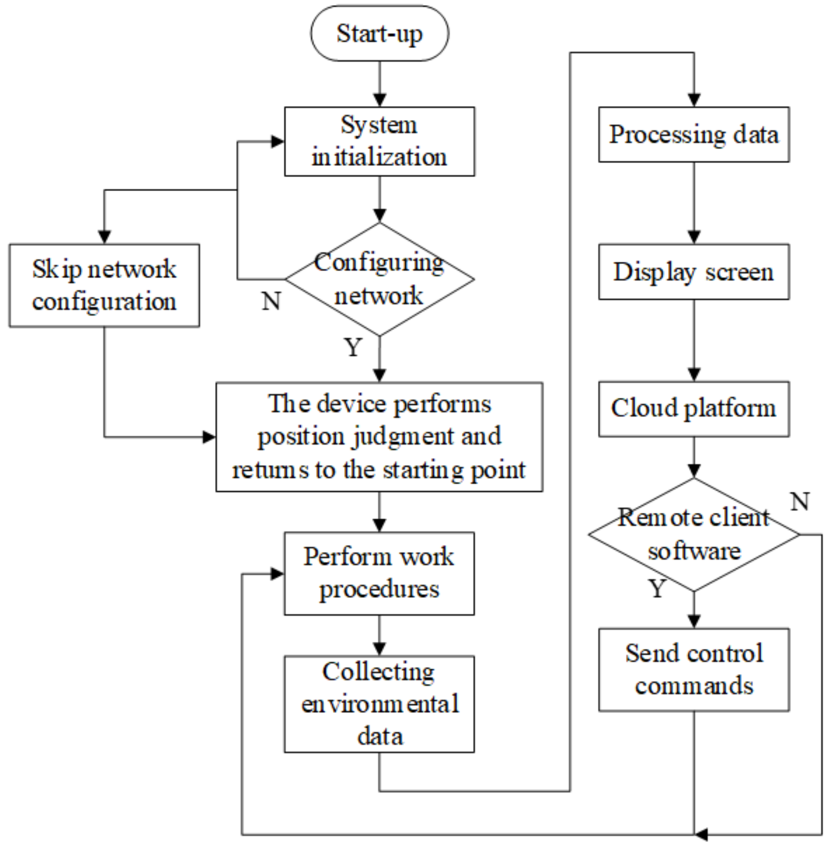



**Figure 9.** Control principle of the main program.

(1) Network

Upon device start, network configuration and location judgment are performed, followed by the device returning to the starting point of the track. Subsequently, the device moves to the designated monitoring site and executes the environmental data acquisition program. The main control module packages the acquired data and sends it to the display screen and remote monitoring terminal for real-time display. During device operation, if the operation manager fails to issue a brake or any other command through the remote monitoring terminal, the device will proceed to the next monitoring point and continue data collection until it reaches the "end-point". In case of a manual mode command from the remote monitoring terminal, the device's working mode switches to the manual, and the administrator can control it remotely through the terminal.

Temperature calibration will be conducted before each sampling process of the robot commences. If there is a temperature difference of more than 5 °C at the calibration position (fixed temperature sensor), it will be considered an abnormal situation, and the system will generate an alarm for the management personnel. During this time, the system does not perform adaptive control but instead switches to a constant standard ventilation mode (no network mode). When other non-control sensors show abnormalities, such as abnormal or extreme values (significantly higher or lower than the set value), the system will send an alarm through the remote client to notify the management personnel of necessary actions.

A single sampling process of a track inspection robot can collect data from multiple monitoring points. The average temperature of multiple environmental monitoring points or a single value from a specific monitoring point can be manually selected as the input value for the control algorithm used in environmental regulation. The system defines a normal temperature range of 22 to 27 °C and an extreme temperature range of 16 to 28 °C. If the value of a certain monitoring point falls within the normal range, the system will operate normally. However, if it exceeds the normal range but still falls within the extreme range, the equipment will continue to operate normally, but the system will send a reminder to the production management personnel. In the case of normal calibration results, if more than 50% of the monitoring points exceed the limit value during a single sampling process, the measuring system will automatically switch to the standard ventilation mode (no network mode) and issue an alarm to prompt human intervention. If less than 50% of the monitoring points exceed the limit value, the system will automatically clear the value and remind the production management personnel.

(2) No network

If the network configuration of the system is skipped manually, the device will enter a no-network state. In this state, the device can only present the environmental data collected on the display screen and cannot receive any instructions from the monitoring terminal.

#### 2.5.2. Network Configuration Program Design

Figure 10 displays the network configuration of the monitoring system in the piggery environment. Upon starting the device, the WIFI module detects the saved WIFI account information. If a matching network is detected, the system automatically establishes a connection and executes the working program after connecting with the server. However, if there is no matching signal, manual network configuration is required. Once a new network signal is connected, the system saves the information for automatic connection in the future.

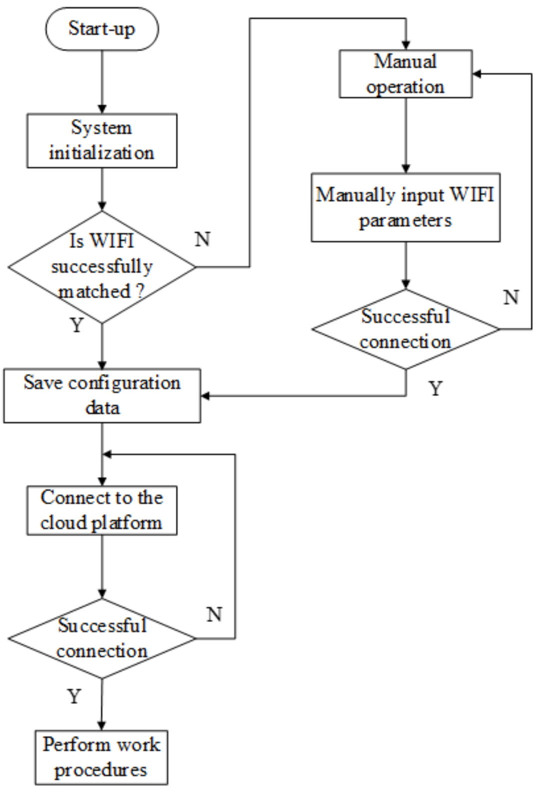



**Figure 10.** Network configuration process.

### 2.6. *Temperature Adaptive Control Design*

An adaptive temperature regulation control algorithm has been designed in conjunction with piggery environmental monitoring and control equipment. The control logic diagram is shown in Figure 11. The temperature for the nursery piggery has been set at 25 °C. If the sensor detects that the actual temperature is higher or lower than the set temperature, the system will utilize the fuzzy PID control algorithm to regulate the temperature control equipment for cooling or heating purposes.

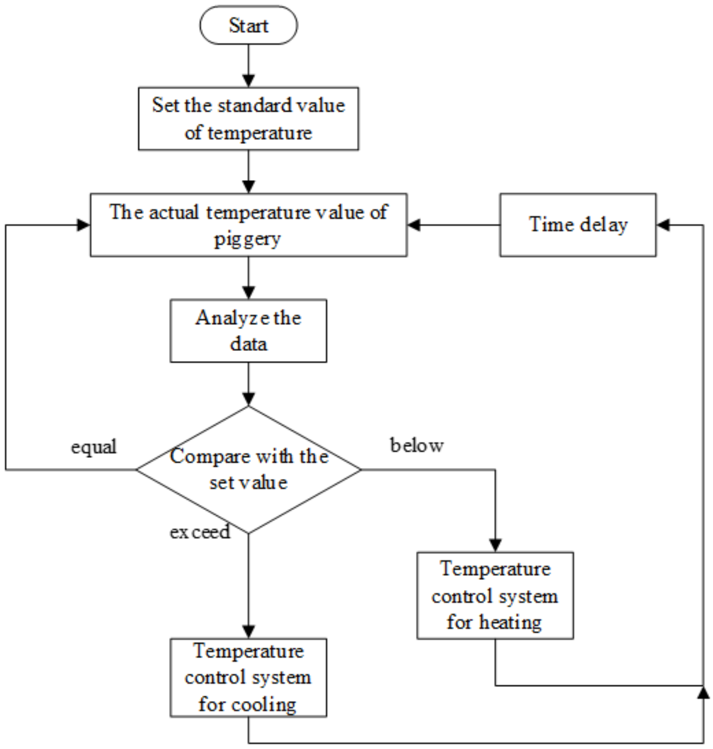



**Figure 11.** Control logic diagram of piggery temperature.

### 2.6.1. Fuzzy PID Controller

The fuzzy PID control algorithm is designed to address the limitations of traditional PID parameters that cannot be adjusted in real-time. This algorithm utilizes specific fuzzy control rules to enable real-time adjustments of PID parameters [31]. The process involves three main steps: fuzzification, determining fuzzy rules, and defuzzification. During fuzzification, the exact value is converted into the corresponding fuzzy linguistic variable value based on the input value of temperature deviation (*e*) and temperature deviation change rate (*ec*) and the fuzzy membership function of the input. Fuzzy inference refers to the process of inference according to specific methods according to fuzzy input and fuzzy rules to obtain the fuzzy output. Defuzzification refers to the process of converting the fuzzy quantity into the accurate quantity, that is, to find out the relationship between the input quantity and the PID parameters, and to adjust it online to realize the optimal configuration of the PID controller. The algorithm logic principle is shown in Figure 12.

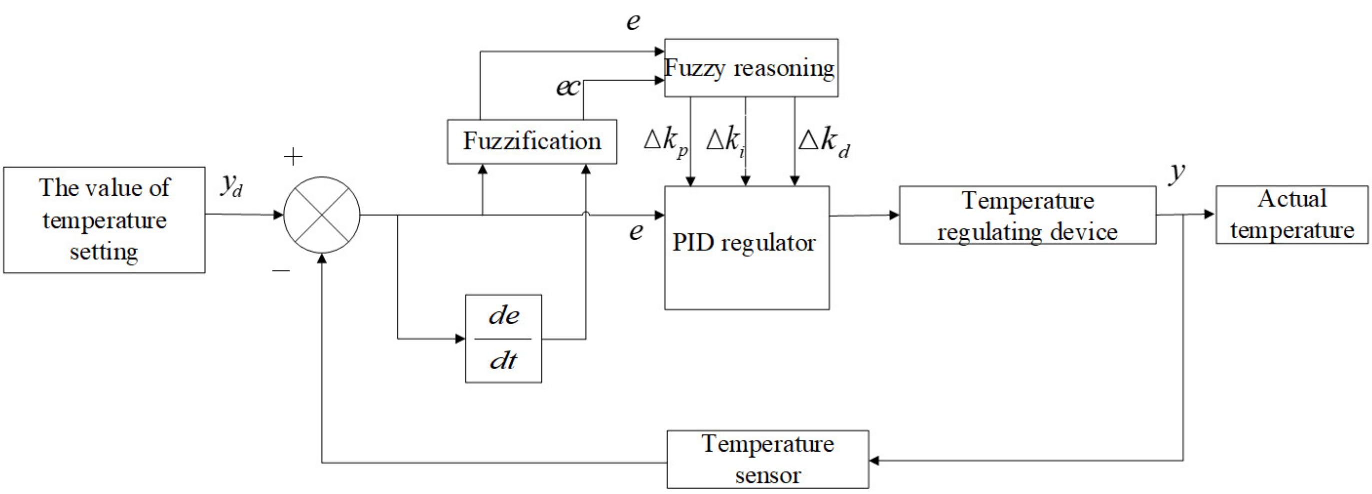



**Figure 12.** Fuzzy PID principle control chart.

According to the change requirements of the environment temperature of the piggery, the basic domain of the piggery temperature deviation ($e$) can be determined as {−3,3}, and the basic domain of the temperature deviation change rate ($ec$) is {−1,1}. After fuzzy reasoning, the basic domain of output proportional coefficient ($\Delta k_p$), integral coefficient ($\Delta k_i$), and differential coefficient ($\Delta k_d$), is {−2,2}, {−0.01,0.01}, {−3,3}, respectively. The domain of fuzzy variables is divided into seven levels, and the corresponding fuzzy linguistic variables are {NB, NM, NS, ZO, PS, PM, PB}. The membership function selects 'trimf'.

Based on extensive practical experience, fuzzy control rules have been established. These rules are then applied to a fuzzy PID controller to perform regular parameter reasoning and obtain actual values for $k_p$, $k_i$, and $k_d$, allowing for online tuning. The PID control method utilizes incremental calculation [32], which is calculated using the following formula.

$$k_p = k_{p0} + \triangle k_p \tag{1}$$

$$k_i = k_{i0} + \triangle k_i \tag{2}$$

$$k_d = k_{d0} + \triangle k_d \tag{3}$$

The proportional coefficient ($k_{p0}$), integral coefficient ($k_{i0}$), and differential coefficient ($k_{d0}$) are the original values, which are set according to practical experience. The fuzzy control rules are shown in Table 2.

**Table 2.** Fuzzy rule control table.

| ***ec*** | ***e*** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **NB** | **NM** | **NS** | **ZO** | **PS** | **PM** | **PB** |
| NB | PB/NB/PS | PB/NB/NS | PM/NM/NB | PM/NM/NB | PS/NS/NB | ZO/ZO/NM | ZO/ZO/PS |
| NM | PB/NB/PS | PB/NB/NS | PM/NM/NB | PS/NS/NM | PS/NS/NM | ZO/ZO/NS | NS/ZO/ZO |
| NS | PM/NB/ZO | PM/NM/NS | PM/NS/NM | PS/NS/NM | ZO/ZO/NS | NS/PS/NS | NS/PS/ZO |
| ZO | PM/NM/ZO | PM/NM/NS | PS/NS/NS | ZO/ZO/NS | NS/PS/NS | NM/PM/NS | NM/PM/ZO |
| PS | PS/NM/ZO | PS/NS/ZO | ZO/ZO/ZO | NS/PS/ZO | NS/PS/ZO | NM/PM/ZO | NM/PB/ZO |
| PM | PS/ZO/PB | ZO/ZO/NS | NS/PS/PS | NM/PS/PS | NM/PB/PS | NM/PB/PS | NB/PB/PB |
| PB | ZO/ZO/PB | NS/ZO/PM | NS/PS/PM | NM/PM/PM | NM/PB/PM | NB/PB/PB | NB/PB/PB |

2.6.2. Temperature Environment Model

According to the characteristics of piggery temperature environment regulation, the mathematical model of the temperature environment is described by using the first-order inertia lag link [4,33–35].

The transfer function can be determined using the following formula.

$$G(s) = Ke^{-\tau s}/(t_0 s + 1) \tag{4}$$

In the formula, $K$, $t_0$, and $\tau$ are the static gain, pure lag time constant, and inertial time constant of the environmental model, respectively. $s$ is a complex variable. According to the energy conservation law, this model ignores the influence of heat production change on pigs and only considers the influence of heat exchange between walls and heat exchange of temperature control systems [36]. The step response curve is determined by inputting the stop signal. The input step signal is 30 °C, and the temperature change value is collected every 90 s. The collected data is shown in Table 3.

**Table 3.** Empty piggery environmental control system temperature rise data.

| **SN** | **Time (s)** | **Temperature (°C)** | **SN** | **Time (s)** | **Temperature (°C)** |
|---|---|---|---|---|---|
| 1 | 0 | 5.2 | 9 | 720 | 19.9 |
| 2 | 90 | 5.9 | 10 | 810 | 22.1 |
| 3 | 180 | 7.1 | 11 | 900 | 23.6 |
| 4 | 270 | 9.4 | 12 | 990 | 25.2 |
| 5 | 360 | 11.6 | 13 | 1080 | 25.5 |
| 6 | 450 | 13.7 | 14 | 1170 | 25.0 |
| 7 | 540 | 15.5 | 15 | 1260 | 25.0 |
| 8 | 630 | 17.8 | | | |

This project uses the two-point method [35,37] to identify the parameters of the temperature transfer function. The sampling points (295, 0.4$y$ (∞)) and (834, 0.9$y$ (∞)) are used to confirm the parameters of the transfer function.

The piggery is tested with step signal input, and the transfer function is shown in Equation (5).

$$U(s) = \frac{30}{s} \tag{5}$$

Determine the step response of its first-order inertial delay link.

$$Y(s) = G(s)U(s) = \frac{30Ke^{-\tau s}}{s(t_0 s + 1)} \tag{6}$$

The inverse Laplace transform of Equation (6) can obtain the original function of time ($t$).

$$y(t) = L^{-1}[Y(s)] = 30K(1 - e^{-\frac{(t-\tau)}{t_0}}) \tag{7}$$

The system gain can be obtained by using the steady-state response value.

$$y(\infty) = \lim_{t\to\infty} y(t) = 30K_1 \tag{8}$$

$$K_1 = 0.83$$

The following parameters can be obtained by substituting two observation data points on the response curve into Equation (7).

$$\begin{aligned} t_0 &= \frac{t_2 - t_1}{\ln[1 - \frac{y(t_1)}{30K_1}] - \ln[1 - \frac{y(t_2)}{30K_1}]} \\ &= \frac{t_2 - t_1}{\ln[\frac{30K_1 - y(t_1)}{30K_1 - y(t_2)}]} = 295 \end{aligned} \tag{9}$$

$$\tau = \frac{1}{2}\{t_1 + t_2 + t_0[\ln(1 - \frac{y(t_1)}{30K_1}) + \ln(1 - \frac{y(t_2)}{30K_1})]\} = 143.58 \tag{10}$$

Finally, the temperature transfer function expression can be obtained as follows:

$$G(s) = \frac{Ke^{-\tau s}}{t_0 s + 1} \approx \frac{0.83}{295s + 1} e^{-143.58s} \tag{11}$$

### 2.6.3. Traditional PID Control Algorithm

This study utilized MATLAB (R2022a) software's Simulink tool to construct a structure diagram of the PID algorithm for controlling the ambient temperature in a piggery. The temperature of the nursery piggery is selected as the control parameter, and the three parameters of the PID controller of the temperature control system are $k_p = 2.19$, $k_i = 0.007$, and $k_d = 73.24$, respectively. Based on the traditional PID control algorithm, the simulation structure is shown in Figure 13. Analyzing the control curve (Figure 14), it is evident that the step function overshoot exceeds 20% after 396 s, but it reduces to less than 2% after 619 s. The large overshoot of the traditional PID in the temperature control model has significant drawbacks.

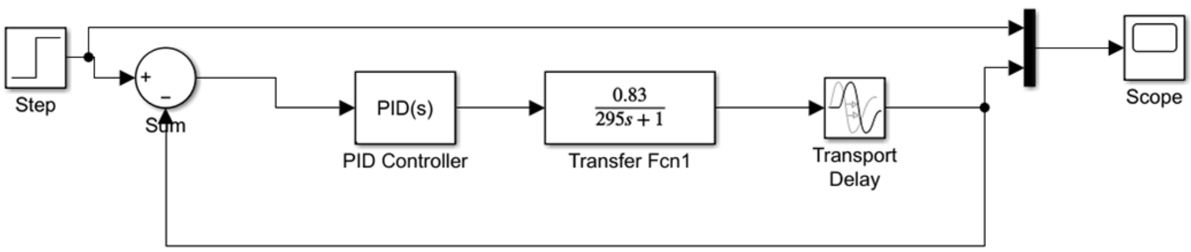



**Figure 13.** Structure diagram of traditional PID control system.

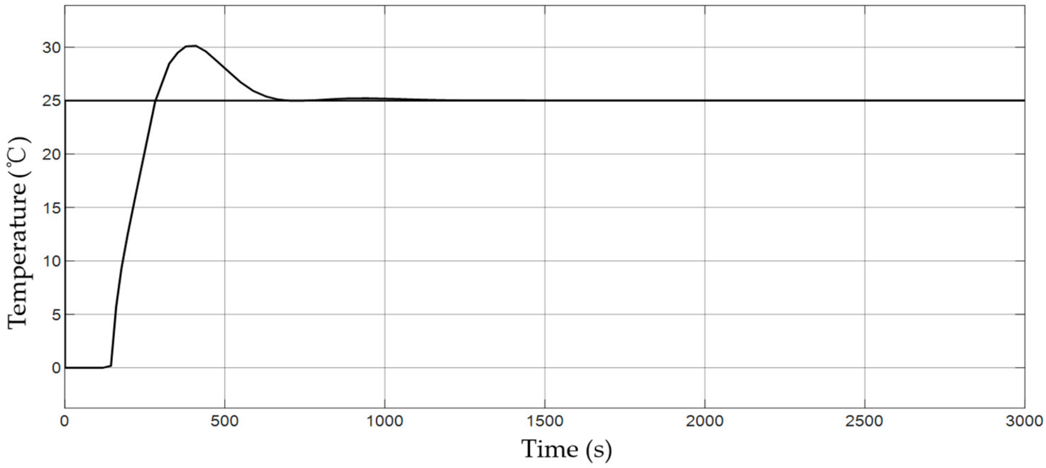



**Figure 14.** The response curve of traditional PID control system.

#### 2.6.4. Fuzzy PID Control Algorithm

Simulink was utilized to construct a fuzzy PID algorithm for controlling the ambient temperature of the piggery. Figure 15 displays the algorithm structure, while Figure 16 shows the corresponding simulation curve. Although the traditional PID control algorithm has a stable control effect in terms of response speed and static error, the overshoot is too high. The simulation model shows that the adaptive fuzzy PID control algorithm has a lower overshoot of only 4%, which is an 80% reduction compared to the traditional PID control algorithm. The overshoot remains at 4% for 502 s and drops below 2% after 714 s. Although the fuzzy PID control algorithm takes an additional 95 s to reach an overshoot of less than 2%, it is more suitable for piggery temperature control due to its lower overshoot.

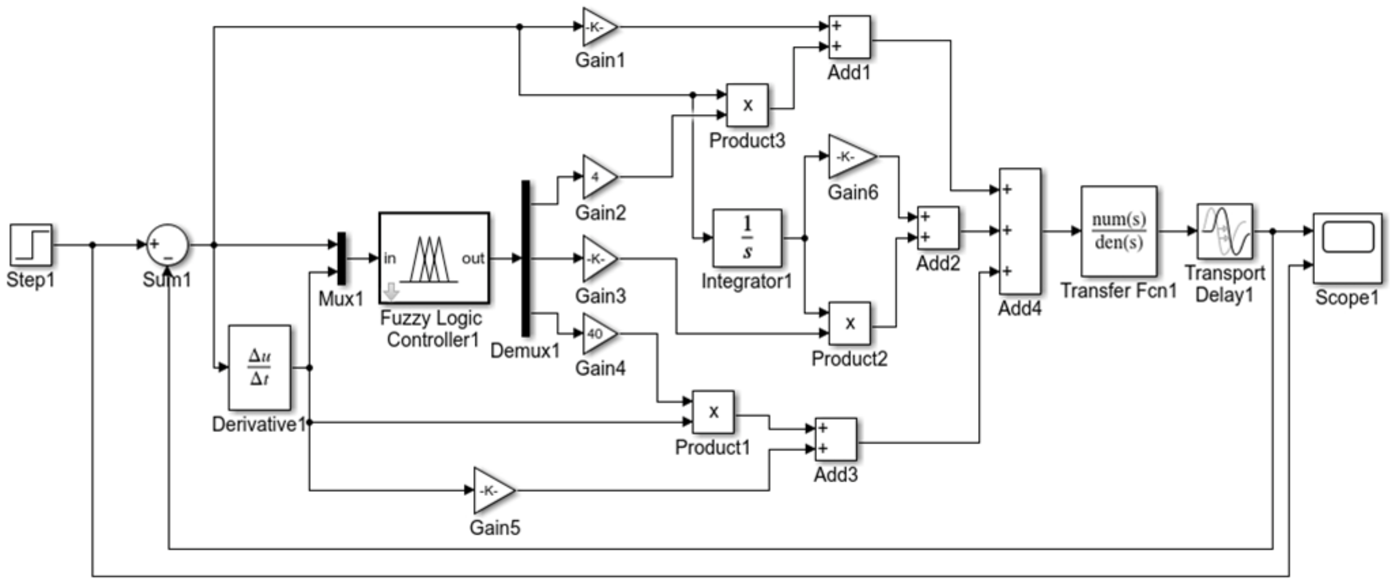



**Figure 15.** Fuzzy PID control system structure diagram.

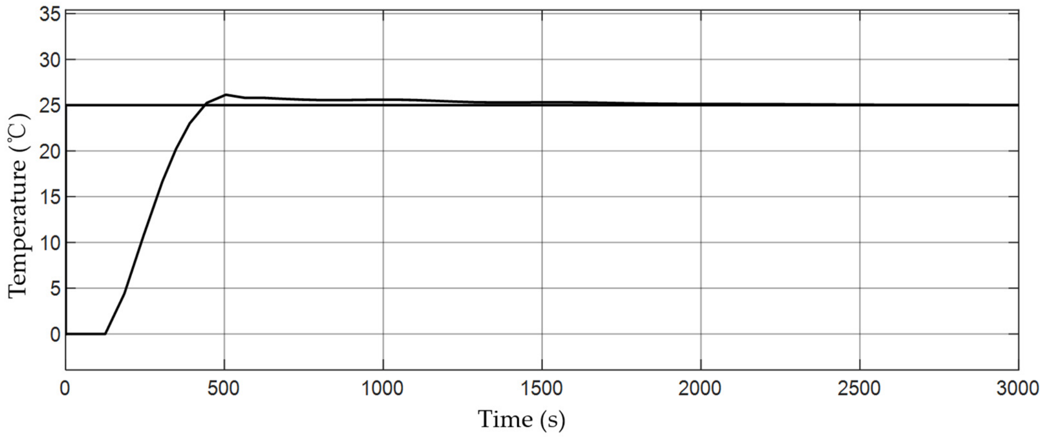



**Figure 16.** The response curve of fuzzy PID control system.

## 3. Results and Discussion

### *3.1. Results*

The system test was conducted on the closed nursery piggery of Juhenongmu Co., Ltd. in Hebi City, Henan Province, China. Environmental parameters were collected by a track inspection robot at two monitoring points, as shown in Figure 1. The data was collected at a height of 90 cm and 150 cm from the ground. The on-site work details of the environmental control system can be seen in Figure 17. Since the weather conditions were stable during the study and there were repetitive data, representative 24 h data from 12–17 April 2023, was selected for display. The outdoor temperature during the test ranged from 10 to 24 °C, with an average relative humidity of about 40%. The system operation test and environmental control effect test were conducted at this stage.

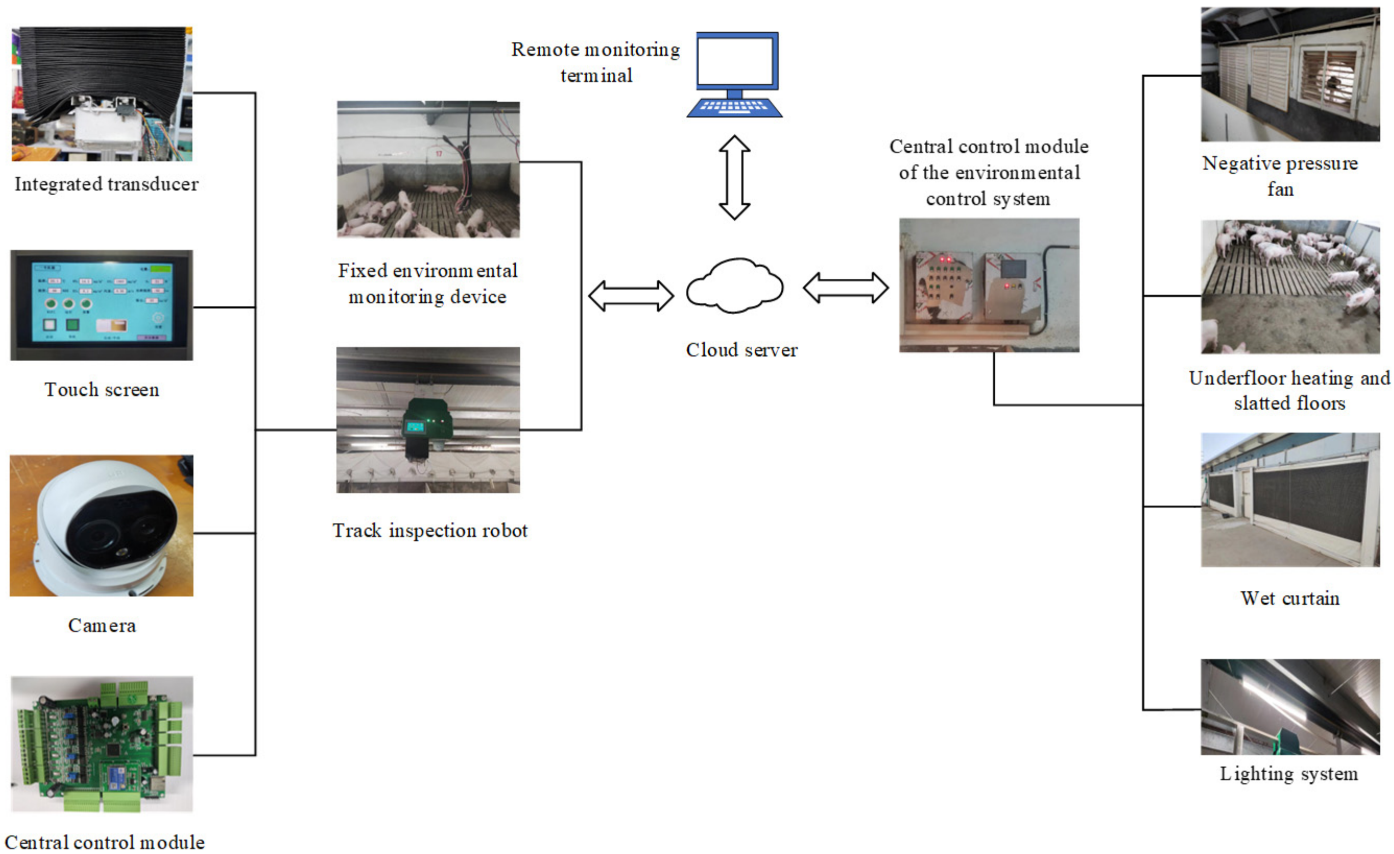



**Figure 17.** Physical map display of the environmental control system.

(1) System operation test

Throughout the test, the control system demonstrated stable performance, as depicted in Figure 18, which shows the human–computer interaction interface (eight-inch serial port touch display screen from Zhongxian Technology Co., Ltd. in Wuhan, China). The track inspection robot was able to precisely identify the monitoring site and autonomously determine its location. The robot's average moving speed was measured at 0.24 m·s$^{-1}$, while the lifting mechanism's speed was 3.8 cm·s$^{-1}$. Additionally, the sensors' sampling time was recorded at 3 min. After 24 h of operation testing, the monitoring point recognition accuracy reached 100%. There were no instances of overheating alarms in the internal circuit components, and no snapping phenomenon was observed during cornering. The remote monitoring terminal (Redmi K40) data transceiver was functioning normally, and the visual interface (Figure 19) provided a better display of the system's running state. The system did not experience any significant delays in sending and receiving instructions.

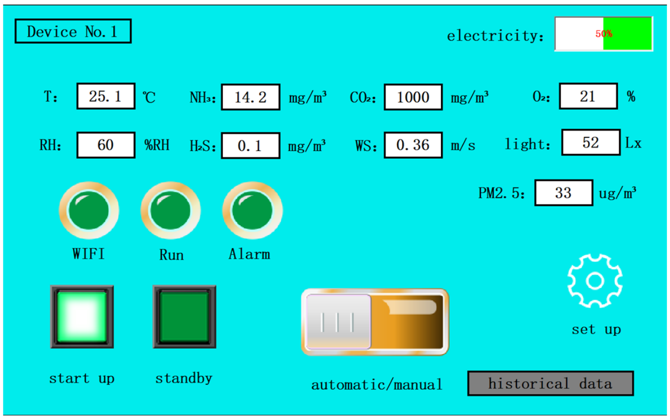
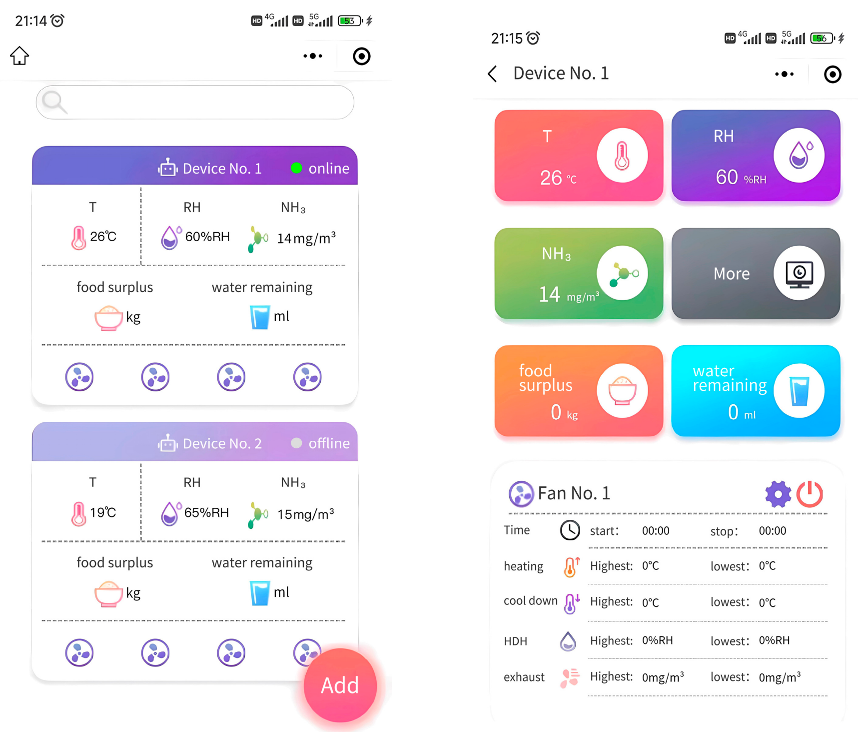



**Figure 18.** Human–Computer interaction interface.




(**a**) (**b**)

**Figure 19.** Mobile phone display interface (WeChat applet). (**a**) Remote monitoring terminal home page; (**b**) Device details page.

The usability test results of the remote monitoring terminal were as follows:

Functional Test Results: In the system, there have been no reported operation failures or delayed reminders in remote control of equipment, display of sensor data, adjustment of on-site environmental equipment, or other related remote operations.

Functional Integrity Assessment: The system was designed and developed in accordance with the enterprise's requirements, and it offers a comprehensive range of functions. Thus far, no negative feedback has been received from the enterprise.

User Interface Test Results: The page layout setting conforms to the operating habits of most farms. The user navigation is simple and direct, and the font color is clear and easy to read.

Performance Test Results: The average response time for opening the remote client page is approximately 4 s. Similarly, the average time for switching between pages is about 1 s. Additionally, the average response time for the remote device is between 2 to 3 s.

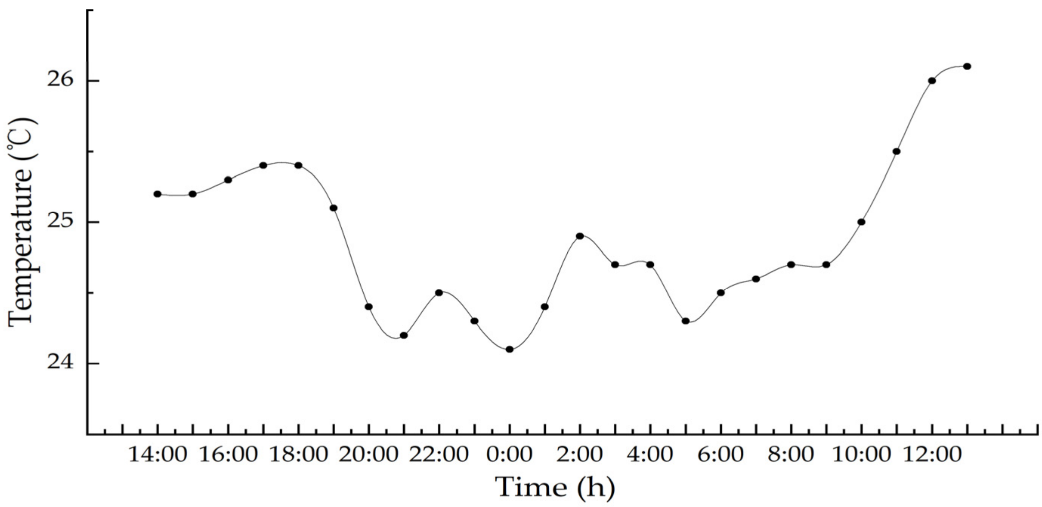
Compatibility Test Results: The remote monitoring terminal has demonstrated stable performance on Android phones such as Vivo, Xiaomi, and Oppo, with no issues regarding confusing or unusable interfaces. Testing on mobile phones of different systems and brands will be conducted in the subsequent stages.

Safety Test Results: The remote monitoring terminal is implemented using the ONEnet cloud server, which guarantees the security of data transmission and storage.

(2) Environmental control

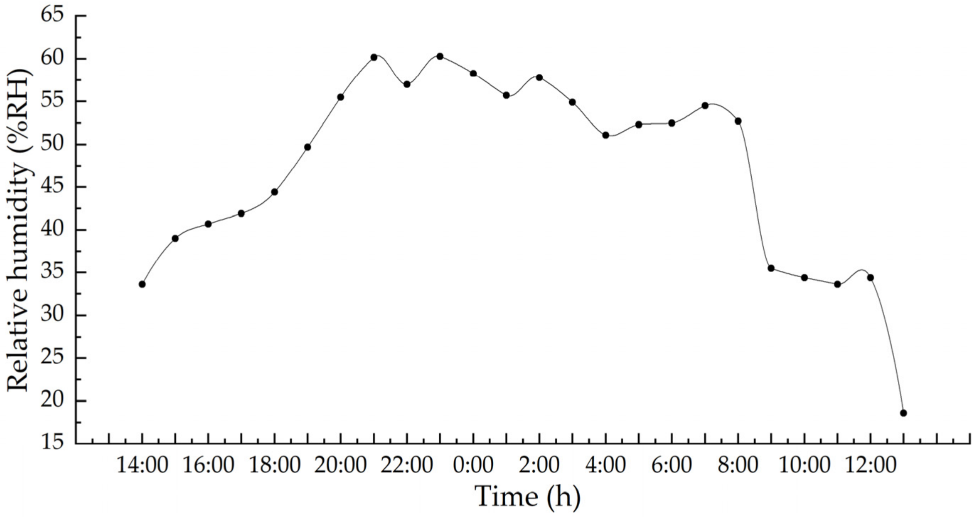
Since 1 April 2023, the device has undergone various tests, which include problems such as the heating of electronic components and the vibration of mechanical structures. During the test phase, because the weather conditions are relatively stable, the test data is highly repeatable. According to the actual situation on site, representative 24 h environmental data were selected for display. To better analyze the environment of the piggery, data from the No. 1 monitoring point, located 90cm from the ground, were selected for analysis. The results are shown in Figure 20.

The findings were analyzed in conjunction with Figure 20 and Table 4. The results of Figure 20a show that the highest temperature recorded was 26.1 °C, and the lowest was 24.1 °C, with a temperature difference of 2 °C and a maximum deviation of 4.4%. The temperature in the piggery is predominantly influenced by outdoor sunlight, particularly from 10:00 to 18:00, resulting in significantly higher temperatures compared to other periods. However, the control process remained relatively stable.

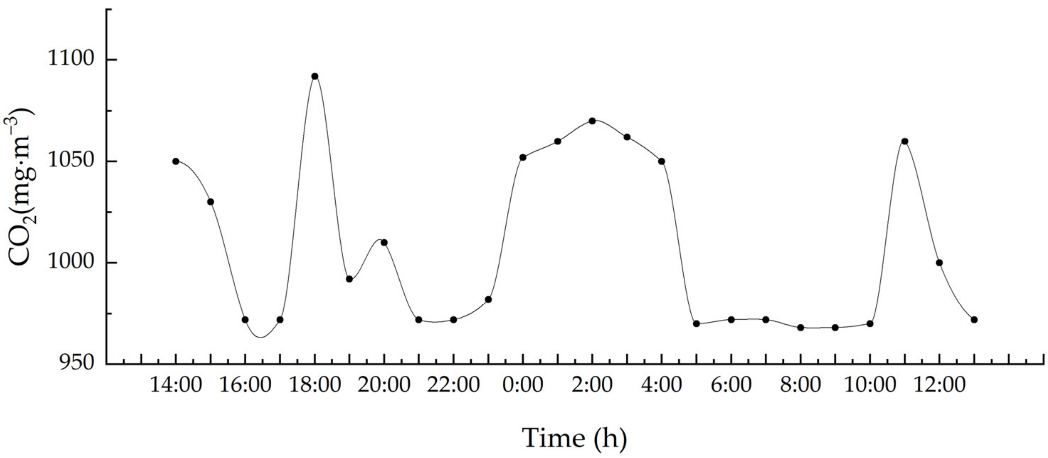



(**a**)

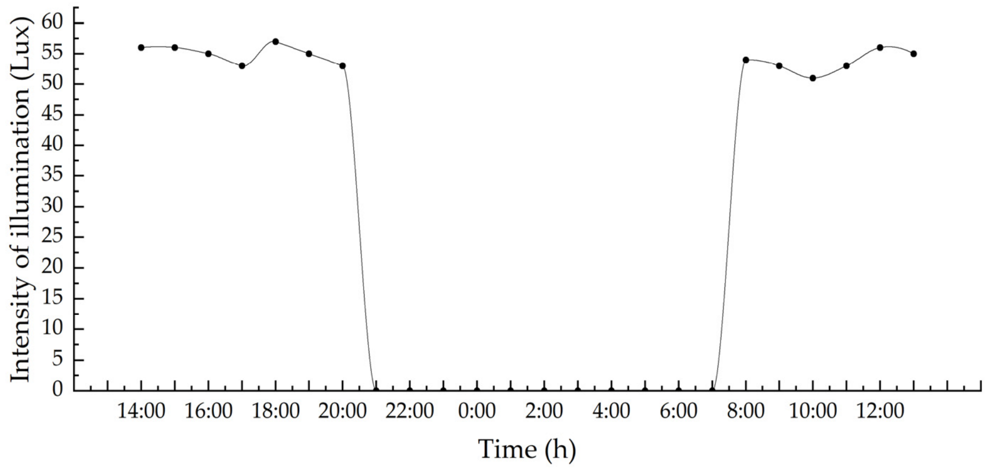
**Figure 20.** *Cont.*




(**b**)

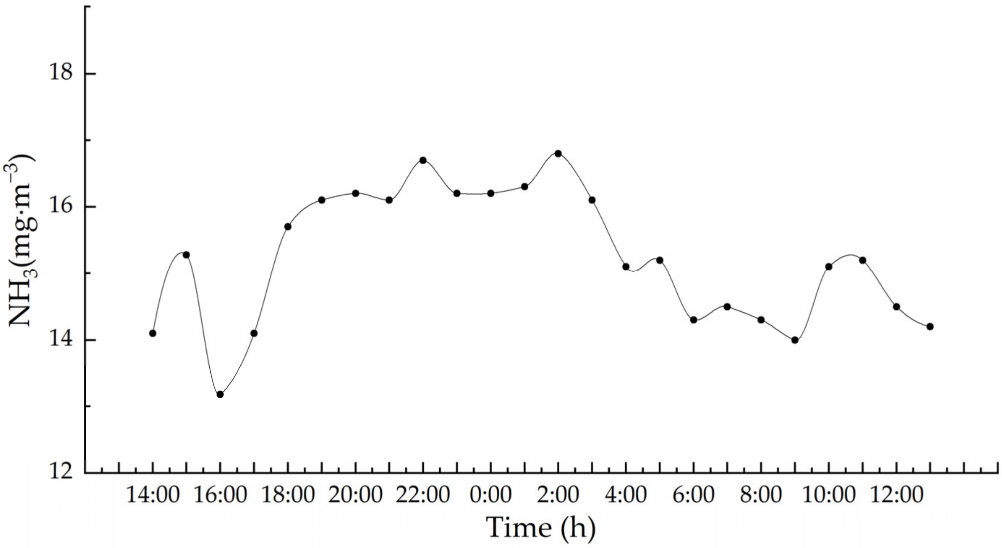



(**c**)

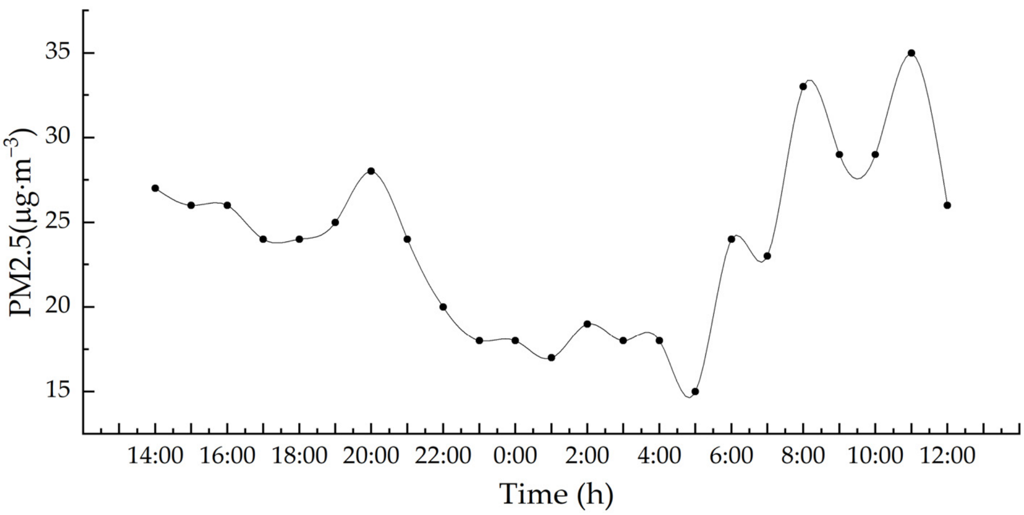



(**d**)

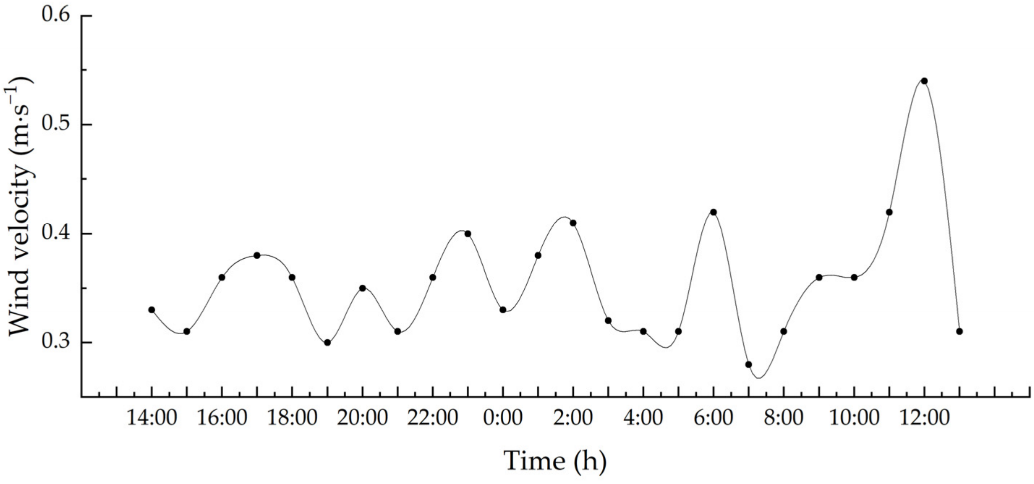
**Figure 20.** *Cont*.




(**e**)




(**f**)




(**g**)

**Figure 20.** Environmental data trends. (**a**) Temperature; (**b**) Relative humidity; (**c**) $CO_2$; (**d**) Intensity of illumination; (**e**) $NH_3$; (**f**) PM2.5; (**g**) Wind velocity.

**Table 4.** Environmental requirements for nursery piggery.

| Environmental Factor | Parameter Ranges | |
|---|---|---|
| temperature (°C) | 16~28 | |
| relative humidity (%RH) | 50~80 | |
| $NH_3$ ($mg{\cdot}m^{-3}$) | $\leq$ 20 | |
| $H_2S$ ($mg{\cdot}m^{-3}$) | $\leq$ 8 | |
| $CO_2$ ($mg{\cdot}m^{-3}$) | $\leq$ 1300 | |
| Dust ($mg{\cdot}m^{-3}$) | $\leq$ 1.2 | |
| wind velocity ($m{\cdot}s^{-1}$) | winter: 0.20<br>summer: 0.60 | |
| intensity of illumination (Lux) | natural lighting | window–floor ratio: 1:10<br>additional illumination: 50~75 |
| | artificial illumination | illuminance: 50~100<br>light exposure time $h^{-1}$: 10~12 |
| Noise (dB) | $\leq$ 80 | |

In Figure 20b, it is observed that the highest humidity recorded was 60.3% RH, the lowest was 18% RH, and the humidity difference is 42.3% RH. This difference is greatly influenced by temperature and exhibits a negative correlation. The relative humidity is lower during high temperatures, especially between 10:00 and 18:00. The low humidity in the house can be attributed to two main reasons. Firstly, the humidification function of the wet curtain only triggers when the temperature reaches 28 °C. Secondly, the colored steel tiles used for the roof of the piggery absorb excessive light intensity at noon, causing a rapid increase in the temperature of the piggery and evaporation of water in the house. Therefore, in these particular cases, to ensure relative humidity stability in the piggery, it is necessary to humidify separately for a specific period.

The concentration of $CO_2$ in Figure 20c is 1092 $mg{\cdot}m^{-3}$, which is below the standard value and meets the environmental requirements of the nursery piggery. Figure 20d shows that the light is turned off from 21:00 to 7:00, and the light intensity is maintained at 51~57 Lux during other times. Table 4 confirms that illumination time and intensity meet the requirements. In this experiment, the content of $H_2S$ was far lower than the standard value, as it was 0 $mg{\cdot}m^{-3}$ in most periods, which had little effect on the health of pigs, so it was no longer described. According to Figure 20e, the maximum concentration of $NH_3$ was 16.8 $mg{\cdot}m^{-3}$. The trend shows a positive correlation with relative humidity, but the values remained relatively stable without significant changes. This concentration level is within the environmental control standards of nursery piggeries.

The variation range of PM2.5 in Figure 20f is 15~35 $\mu g{\cdot}m^{-3}$, which is far lower than the standard value and meets the environmental requirements of the nursery piggery. The wind speed in Figure 20g is maintained at about 0.35 $m{\cdot}s^{-1}$, the highest value is 0.54 $m{\cdot}s^{-1}$, and the difference is 0.24 $m{\cdot}s^{-1}$. The overall trend is relatively stable. The wind speed peaked at about noon, mainly due to the relatively high temperature during this period. By increasing the wind speed to achieve the purpose of cooling, it generally meets the ventilation requirements of the nursery piggery in the summer. According to the collected data, it can be seen that the environment of the nursery piggery created by the control system can better meet the standard of Environmental Parameters and Environmental Management of Large-scale Pig Farms [38] (Table 4). However, it is necessary to cooperate with the humidification device in the nursery piggery to meet the humidity control standard.

### 3.2. Discussion

(1) Environmental control analysis of piggeries under different seasons and humidity

Based on the experimental results, it is evident that temperature, humidity, and ammonia concentration exhibit periodic fluctuations throughout the day. The fuzzy PID control system, which is based on temperature control, demonstrates stable performance and effective environment regulation in the nursery piggery. In different seasons, if there is a larger difference between the outdoor ambient temperature and the set value, it may result in an extended temperature regulation time. However, it remains within a manageable range, making it unnecessary to collect and analyze data for each season. In order to address the significant environmental temperature changes that occur between different seasons, the fuzzy PID (Section 2.6.1) incorporates a comprehensive fuzzy control rule table (Table 2) that takes into account all potential variations in the environment.

Because there is no separate humidity control equipment in the experimental piggery, the system was not designed to control it during the development process. Based on previous studies, it has been observed that temperature and $NH_3$ are crucial parameters for environmental control. Furthermore, these two factors exhibit a strong correlation, as indicated by a correlation coefficient of 0.787 [39] and the mainstream control scheme primarily focuses on temperature. Additionally, the humidity in the closed piggery is only low between 12:00 and 14:00. To meet the environmental requirements of the piggery, other humidification measures such as ground watering can be used.

The system is currently capable of detecting humidity. However, the system can easily achieve adaptive control of humidity by incorporating the PID control algorithm, which follows the same principle as temperature control, and connecting it with relevant equipment.

(2) Innovation and advantages

Compared to the traditional fixed environmental monitoring system, the environmental control system based on the track inspection robot significantly reduces the number of sensors required. The system effectively reduces the cost of the sensor and simplifies the wiring process, while maximizing the sensor's utilization rate.

According to the piggery monitoring standard, a new eight-in-one transducer has been developed. This transducer includes measurements for temperature and humidity, ammonia, carbon dioxide, wind speed, PM2.5, hydrogen sulfide, and light intensity. It is considered more advanced and comprehensive compared to the five-in-one transducer currently available in the market.

The track inspection robot has the capability to adjust the monitoring height according to different monitoring scenes. The monitoring position can be adjusted according to the breathing position of the animals being monitored.

Compared to the current wheeled monitoring robot, the track inspection robot offers a lower cost and eliminates the need for path planning. Consequently, it is more suitable for closed farming scenarios with complex road conditions.

(3) Application Prospect

The system is specifically designed and developed to cater to the needs of complex environments, such as farming. It is important to note that pigs in different growth stages have varying environmental requirements. However, the monitored environment type remains the same. Therefore, it is only necessary to adjust the control standard of environmental parameters within the system to ensure compliance with the desired control requirements.

Different livestock has different requirements in terms of growth environment, so it is only necessary to adjust the monitoring position, and it is possible to monitor the environment of closed chicken houses or dairy cow houses. In a closed-cage chicken house, each floor should be monitored according to the height of the cage, and three positions in the front, middle, and rear of the chicken house should be monitored. For closed free-range chicken houses and cow houses, the monitoring position should be set according to the breathing height of the livestock. For open livestock houses, only cameras are used for inspection, and environmental monitoring is of little value.

(4) Cost analysis

The total initial investment is CNY 71,000. The equipment cost of the environmental control system is CNY 40,000 (including sensors, cameras, touch screens, other electronic components, and casings, etc., excluding environmental control equipment), and the initial sales price is CNY 60,000; PLC, wiring, and labor cost is CNY 4000; cloud server is CNY 2000;

other costs are CNY 5000. The service life is calculated on the basis of 5 years, and the average annual maintenance cost (Sensor calibration, replacement, circuit maintenance, etc.) is about CNY 2000. The average power of the track inspection robot in the running state is approximately 130 W. In this project, the track inspection robot operates for approximately 16 h per day and consumes a total of about 2 kWh of power. The cost of electricity for planting and breeding is estimated to be around CNY 0.7 per kilowatt-hour, resulting in an annual expenditure of approximately CNY 511. Based on the above calculations, the average annual investment of the project is CNY 16,711. It is important to note that the actual size of the pig house may differ from this project, and the mentioned equipment and electricity charges should be considered as reference values. In most cases, the subsequent maintenance is primarily focused on the sensor. The cost of sensors constitutes a significant portion of the initial investment. Compared with traditional fixed-point monitoring, this monitoring system greatly reduces the cost of sensors.

(5) Environmentally friendly material

The mechanical structure and shell of the robot are constructed using ASTM (American Society of Testing Materials) 304 metal materials, while the surface coating is applied with non-toxic water-based paint. All plastic parts are made of environmentally certified materials (polyethylene, PE). The sensors are certified for environmental protection, ensuring that they do not have any adverse effects on the environment or the pigs. In case of any failed sensors, a dedicated professional department is responsible for their recycling. No parts contain POPs (Persistent Organic Pollutants) or VOCs (Volatile Organic Compounds).

(6) Potential Challenges

Based on theoretical calculations, the current equipment is capable of supporting the operation of a single piggery with a maximum area of 400 $m^2$. After this area is exceeded, the area of the piggery needs to be divided into regions, and multiple devices can be partitioned and run at the same time. In the remote monitoring terminal, multiple devices are permitted to access and can be managed individually.

When it comes to piggeries larger than 400 $m^2$, the main challenge lies in finding ways to enhance the operational efficiency of the equipment, thereby minimizing the need for additional investments in equipment. To overcome this problem, there are the following two solutions.

(1) Optimize the mechanical structure and power system of the equipment to achieve the goal of increasing speed.
(2) On the basis of the control system, a certain number of fixed monitoring devices or tracking inspection robots are added, and the method of shortening the moving distance of the track inspection robots is adopted to achieve the purpose of rapid monitoring.

In conclusion, the product is reliable and can meet the basic environmental needs of piggeries. Compared with the traditional environmental control system, it has better flexibility. The system can be adjusted to meet the specific application requirements of the enterprise, making it highly valuable for promotion purposes. The system has a wide range of applications and can be used in various settings such as chicken houses, cowsheds, and greenhouses. The materials used by the track inspection robot are all environmentally friendly materials.

## 4. Conclusions

This study presents a novel environmental monitoring system using a multi-sensor track inspection robot. The system aims to monitor multiple environmental factors and improves upon the traditional fixed-site monitoring method. The system consists of a mobile monitoring platform, an environmental control system, and a remote monitoring terminal, which together form a closed-loop monitoring system. To evaluate the system, a 24 h equipment test was conducted in a closed nursery piggery. The characteristics of the equipment are as follows:

(1) The control circuit based on an AVR single-chip microcomputer operates reliably, and no overheating alarms were detected in the internal circuit components.
(2) The recognition accuracy of environmental parameters at the monitoring points is 100%. The equipment has an average moving speed of 0.24 $m \cdot s^{-1}$ and a monitoring height range of 0 to 1.5 m. The lifting mechanism has a lifting speed of 3.8 $cm \cdot s^{-1}$, and the sensor takes an average sampling time of 3 min.
(3) The human–computer interaction module and the remote management system can monitor the environmental parameters, adjust the equipment's operation, and provide management functions for data recording and downloading.
(4) The adaptive fuzzy PID control algorithm incorporates the environmental control system, enabling it to dynamically regulate the temperature in the piggery. Additionally, it collaborates with the humidification device to ensure compliance with the environmental standards of the nursery piggery.

In summary, the control system and the humidification device cooperate with each other, and through the adjustment of temperature, it can meet the basic environmental conditions of breeding places such as closed pig houses. The control method is simple and effective, which can realize the application requirements of on-site unmanned management and has a good application prospect. The motion mechanism adopts a semi-closed structure, which is easily corroded by dust. When the system does not trigger the water curtain humidification and cooling function, the lower limit of relative humidity control is not very ideal, which needs to be further improved in subsequent development.

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**Data Availability Statement:** The data that support the findings of this study are available from the corresponding authors upon reasonable request.

**Conflicts of Interest:** The authors declare no conflict of interest.

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