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Development of a Precision Feeding System with Hierarchical Control for Gestation Units Using Stalls

Jingjing Xia [1,2], Jichen Xu [1], Zhixiong Zeng [1], Enli Lv [1,*], Feiren Wang [2], Xinyuan He [1] and Ziwei Li [1]

[1] College of Engineering, South China Agricultural University, Guangzhou 510642, China; xiajingjing@gdmec.edu.cn (J.X.); zhixzeng@scau.edu.cn (Z.Z.)
[2] Schools of Automobile, Guangdong Mechanical and Electrical Polytechnic, Guangzhou 510550, China; 2020010018@gdmec.edu.cn
* Correspondence: enlilv@scau.edu.cn; Tel.: +86-20-8528-2860

Abstract: To obtain good productive performance, sows have different nutrition requirements at different gestation periods. However, in gestation stalls, conventional feeders have large relative errors, management is difficult because of the large numbers of sows, and there are shortcomings in feeding precision and data management. In order to achieve precision feeding and enhance the control of multiple feeders for gestating sows housed in stalls, this study was carried out to investigate a precision feeding system that could be controlled at multiple levels. This system consisted of an electronic sow feeder (ESF), controller area network (CAN), personal digital assistant (PDA), central controller, and Internet of Things platform (IoTP). The results of the experiment showed that relative errors of 60 ESFs delivering feed were within ±2.94%, and the coefficient of variation was less than 1.84%. When the received signal strength indicator (RSSI) ranged from −80 dbm to −70 dbm, the packet loss rate of the PDA was 3.425%. When the RSSI was greater than −70 dbm, no packet loss was observed, and the average response time was 556.05 ms. The IoTP was at the performance bottleneck when the number of concurrent threads was greater than 1700. These experimental results indicated that the system was not only highly accurate in delivering feed, but was also highly reliable in the transmission of information, and therefore met the production requirements of an intensive gestation house.

Keywords: gestating sow; precision feeding; CAN; PDA; IoT platform

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Citation: Xia, J.; Xu, J.; Zeng, Z.; Lv, E.; Wang, F.; He, X.; Li, Z. Development of a Precision Feeding System with Hierarchical Control for Gestation Units Using Stalls. *Appl. Sci.* **2023**, *13*, 12031. https://doi.org/10.3390/app132112031

Academic Editors: Dolores Parras-Burgos, José Miguel Molina Martínez, Ginés García-Mateos and Yutaka Ishibashi

Received: 5 September 2023
Revised: 28 October 2023
Accepted: 30 October 2023
Published: 4 November 2023

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1. Introduction

Globally, there is an increasing demand for animal products (e.g., meat, dairy products, eggs, wool, leather, etc.) [1–4]. African swine fever [5] and excessive population growth [6,7] have brought new challenges, requiring pig husbandry to further develop in the direction of intensification, specialization, and refinement [8,9].

Feed costs account for a major proportion of the total cost of raising pigs [10]. Reducing feed waste helps to mitigate the world food crisis, as well as reduce the costs of pork production [11,12]. The appropriate feeding allowance should be determined at various gestation stages [13,14], as inadequate or excessive feeding can compromise the reproductive performance of sows [15]. The gestation period of sows is typically categorized into three stages. During early gestation, there is no clear benefit observed from increased feeding [16], and excessive nutrient intake may lead to higher embryo mortality and lower litter sizes [17]. In mid-gestation, gilts are still growing and developing, and sows need to recover body reserves lost from the previous breeding cycle [18]. Late gestation is a period for improving the birth weight of piglets [19,20]. Increasing the energy intake of sows has a positive effect on individual piglets, but may also elevate the stillborn rate [21].

The implementation of precision feeding has a positive impact on the sustainability of pig husbandry [22,23]. Compared with conventional feeding, precision feeding decreases

the intake of lysine and protein and reduces feed costs without adversely affecting growth and reproductive performance [24–26]. Additionally, in terms of environmental protection, precision feeding reduces nitrogen and phosphorus excretion [27,28]. Buis et al. [29] observed that gilts subject to precision feeding ate more and lost less weight during subsequent lactation. Quiniou [30] found that precision feeding decreased the risk of sows being too fat or too thin, thereby decreasing the risk of impaired farrowing or milk production, and also that there was less variability in backfat thickness when sows farrowed in the same batch. Iida et al. [31] showed that the risk of fetal displacement in sows could be identified early by measuring feed intake and time spent at an ESF.

The integrated application of automation and Internet of Things (IoT) technologies in pig husbandry can contribute to more accurate data records [32,33] which in turn reduce the burden on practitioners, lower the cost of farming, and raise productivity. The IoT connects physical objects and spaces into a local area network or internet and enables efficient monitoring and management by integrating data objects [34–36]. Zeng et al. devised a three-layer wireless sensor network system based on ZigBee to monitor four environmental parameters (temperature, relative humidity, and concentrations of carbon dioxide and ammonia) in commercial gestation units; real-time monitoring of the microclimate and timely intervention were achieved by analyzing the temporal and spatial characteristics of the pigsty [37]. Lee et al. developed a monitoring system using wireless broadband leaky coaxial cable to collect data from Bluetooth Low-energy (BLE) tags attached to individual pigs. These data were used to compute and estimate the position and movement of each pig [38].

Group housing and conventional stall housing have their own advantages and disadvantages [39,40]; however, because of different degrees of development and economic factors, stalls are still heavily used outside Europe. As part of the transition of intensive pig farms towards automation and informatization, the development of a precision feeding system suitable for stall housing represents a significant step forward. Liu and Xiong et al. designed an electronic feeder for the precision feeding of sows housed in stalls [41,42]. However, there is a scarcity of research examining the shortcomings and defects of precision feeding systems within a real intensive pig farm. We identified these following challenges: (1) it is inconvenient for breeders to adjust the parameters of the ESF, because they have to raise their heads or stand on tiptoe to click buttons attached to ESFs; (2) close contact between breeders, sows, or feed should be avoided to prevent African swine fever; (3) pig farms are usually built in the suburbs with poor wireless network signals, resulting in the frequent disconnection of communication between the ESF and the internet; and (4) the unified management of the ESF is completely reliant on the internet, which is prone to data loss, leading to production errors.

In order to overcome the abovementioned difficulties, we devised a precision feeding system suitable for gestation units using stalls which combined automation, CAN, PDA, central controller, and IoT technologies. In this system, the average performance of 60 lines, and potential correlation between the feeding performance and the location of the feeding line were focused on. The three-level hierarchical control method was introduced: (1) for a Center Controller and all ESFs in a gestation unit, and CAN-based LAN was utilized to unite them; (2) for an individual ESF and a PDA, and WIFI-based LAN was used to establish a connection; (3) for a Center Controller and the IoTP, and the Internet took responsibility to share production data. Live trials were conducted to evaluate the three-level hierarchical control method's performance and reliability.

2. Materials and Methods

2.1. Gestation Sow Housing

The use of stalls is common for intensive pig farms in China. Our experiments were conducted at a pig farm in Sichuan Province, China. The sows were housed in a gestation unit from weaning to 110 days of breeding. The gestation unit consisted of 30 columns, each containing 60 stalls 2.2 m long and 0.65 m wide, and an automatic feed line 2.0 m

above the floor. The feeding system was applied to one of the columns, and each stall was equipped with an ESF. A total of 60 ESFs were used, together with a central controller and a PDA. Figure 1 illustrates part of the environment in which the precision feeding system was implemented.

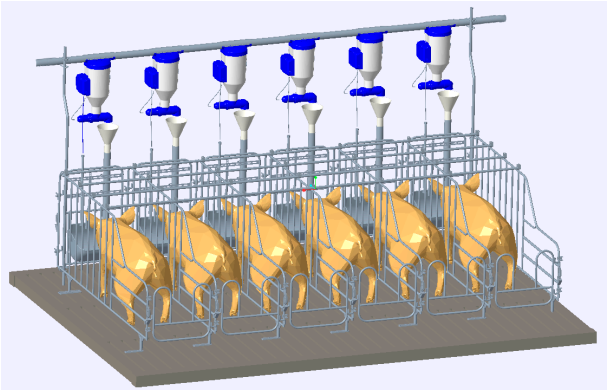


Figure 1. Part of the environment in which the precision feeding system was implemented.

2.2. System Design

2.2.1. Overall Architecture

The precision feeding system for gestating sows was constructed using ESFs, a CAN, a central controller, a PDA, and an IoTP. The ESFs ensured accurate, timed, and ration feeding; the CAN connected all the ESFs and provided a unified management method; the central controller managed the CAN through a graphical interface and uploaded feeding data to the IoTP; the PDA operated individual ESF via an application and WLAN communication; and the IoTP received and displayed device information and feeding data. Figure 2 shows the overall architecture of the system.

2.2.2. Electronic Sow Feeder

The ESFs comprised a delivery mechanism and a control circuit. The delivery mechanism consisted of a plastic bucket, a motor (37GA370SH283011, 24V, 20RPM, Zhejiang Youtuo Motor Co., Ltd., Jinhua, China), and a feeding auger. The electronic circuit included an MCU (STM32F103, ARM), a CAN transceiver module (ISO1050DUBR, Texas Instruments Semiconductor Technology Co., Ltd., Shanghai, China), a WLAN transceiver module (ESP-075, Ai-Thinker Technology Co., Ltd., Shenzhen, China), memory, a buzzer, etc.

Each ESF implemented the following functions: (1) it fed sows at regular intervals according to the programmed scheme; (2) it maintained a connection with the CAN, reported operation status, and received commands from the central controller; and (3) it operated the socket server at the appointed port to communicate with the PDA on a one-to-one basis.

Figure 3 shows the delivery mechanism and the electronic circuit.

2.2.3. Controller Area Network

Because of the large number of ESFs in the gestation unit, there was a need for a control strategy which could cope with multiple devices and manage the devices uniformly and efficiently. CAN is an efficient serial bus communication protocol with characteristics including high communication efficiency, strong anti-interference ability, a node arbitration mechanism, and self-diagnosis of errors. Because gestation units are complex environments with a lot of interference noise, the development of a CAN is highly beneficial for the management of ESF clusters.

2.2.4. Central Controller

The CAN controlled the ESFs via data streams and communication protocols but these could not be intuitively understood by the breeders. The central controller implemented a graphical interactive interface to manage the CAN using a touchscreen, thereby improving the user experience for the breeders. The central controller was equipped with an Intel Celeron J1900 CPU, 4GB RAM and a touchscreen and ran the Windows 7 operating system. The human–computer interaction was developed using the C++ programming language and the Qt5.9 framework. Qt is a cross-platform GUI framework for desktop, embedded, or mobile platforms.

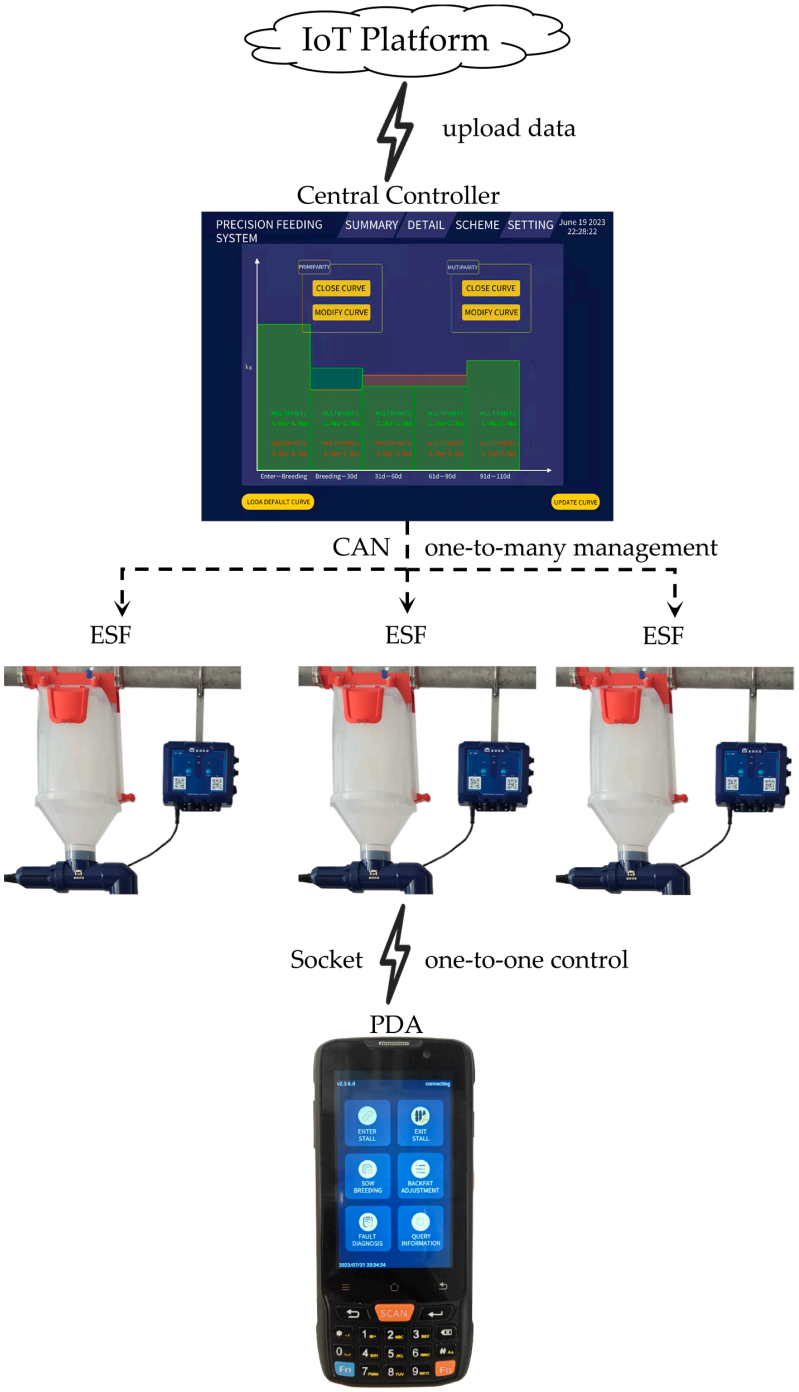


Figure 2. Overall architecture of the precision feeding system with hierarchical control for gestation units using stalls.

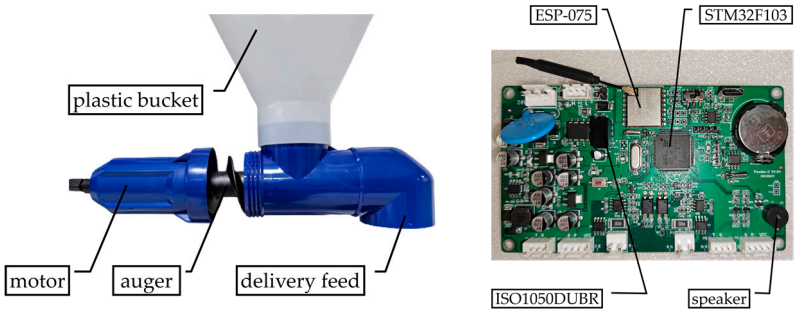


Figure 3. (**a**) Delivery mechanism and (**b**) electronic circuit.

The central controller fulfilled the following functions: (1) it connected the CAN to manage all the ESFs as a master node; (2) it collected the operation status of the ESF as well as the feeding data which were uploaded to the IoTP in HTTP; and (3) it displayed the status of the ESF, presented information, adjusted the feeding scheme, and calibrated the delivery speed. Figure 4 shows parts of the screens.

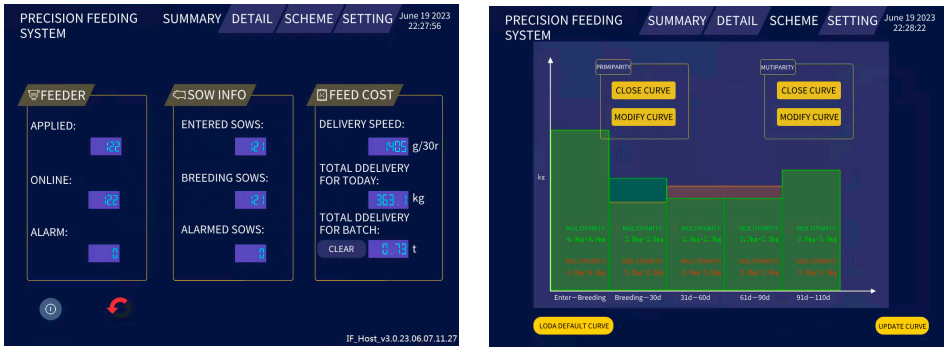


Figure 4. (**a**) Operating status page and (**b**) feeding scheme page.

2.2.5. PDA

The feeding system was regulated as a whole by the CAN, but the ESFs also required a convenient, one-to-one management method. As a type of GUI software with excellent performance and high visibility, Android application technology was used to implement the key functions related to activity, service, broadcast, content provider, and other components. The application running on the PDA (equipped with a laser scanner and Android 8.0 operating system) was developed to manage an individual ESF.

The application includes "ScanReceiver", "ConnectService", communication protocol, function page, and so on. "ScanReceiver" extended "BroadcastReceiver", received the scanning broadcast from PDA, and parsed out the valid content. "ConnectService" extended service, connected to WLAN according to SSID, and established a one-to-one socket pipeline. The communication protocol was employed to safeguard against malicious attacks through message parsing and validation. The function pages served as the gateway to ESF management. Figure 5 illustrates the workflow of using the PDA to manage the ESF. The steps involved for breeders to manage the ESF using the PDA were as follows:

(1) The PDA scanned the QR code attached to the ESF and transferred the byte content to the APP via broadcast.
(2) The content was parsed to extract the Service Set Identifier (SSID), representing the unique WLAN generated by an ESF.
(3) Based on the SSID, the app established a socket pipeline with the ESF.
(4) Breeders could manage the ESF through function pages such as Entry, Exit, Breeding, Backfat Adjustment, Diagnosis and Test, and Information Query pages.

(5) Connectivity between the app and ESF had to be maintained. If the ESF did not receive a heartbeat from the app every 3 s, it would interrupt the connection to prevent data inconsistency.

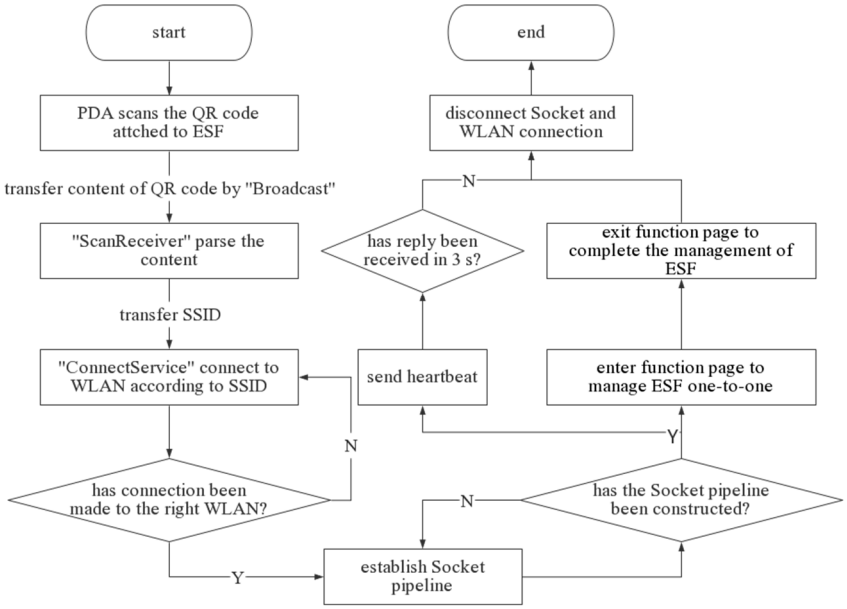
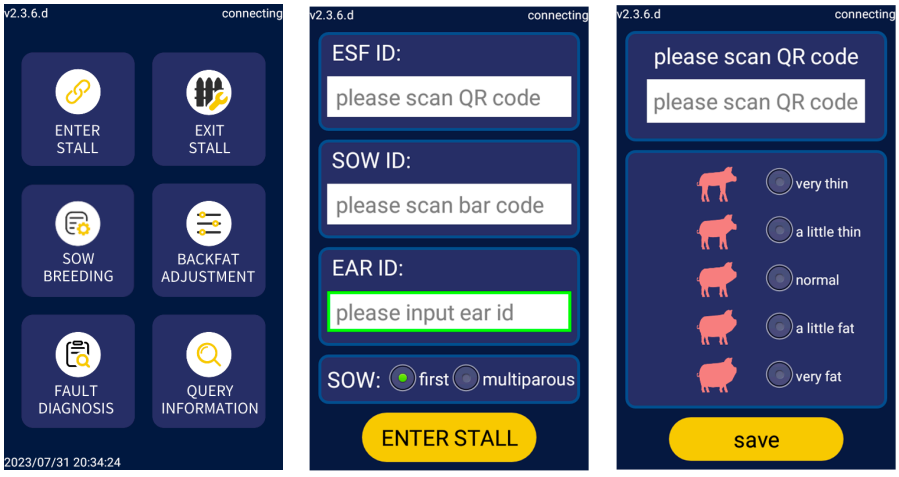


Figure 5. Workflow of PDA management of ESF.

Figure 6 displays some of the PDA screens, each with specific responsibilities:

(1) The "ENTER STALL" page facilitated the association between a sow and an ESF.
(2) The "EXIT STALL" page allowed for the disassociation between a sow and an ESF.
(3) The "SOW BREEDING" page enabled inputting mating date to adjust the feeding scheme accordingly.
(4) The "BACKFAT ADJUSTMENT" page allowed input of the backfat thickness to notify the ESF to update the feeding scheme.
(5) The "FAULT DIAGNOSIS" page provided a means to query fault information related to the ESF.
(6) The "QUERY INFORMATION" page provided functionality to inquire about the sow's status.



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

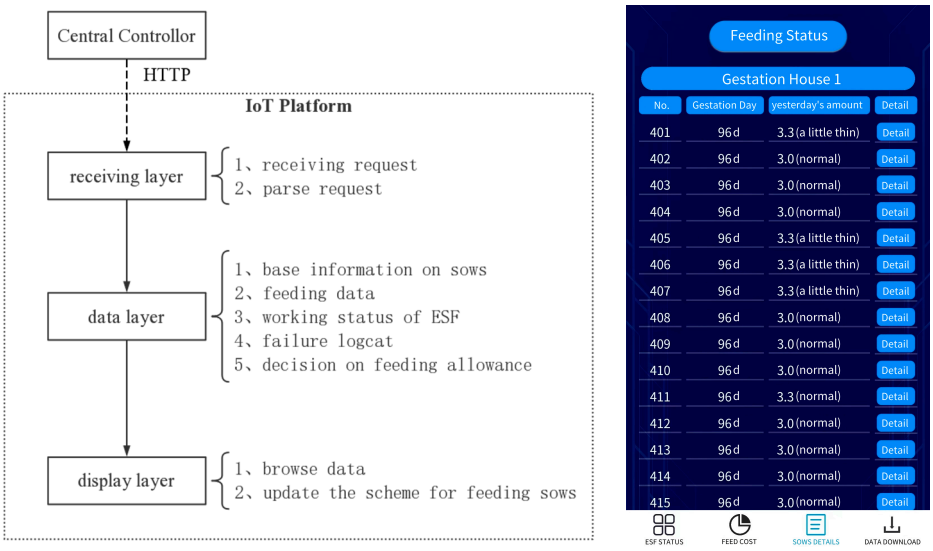
Figure 6. (**a**) Home page, (**b**) "ENTER STALL" page, and (**c**) "BACKFAT ADJUSTMENT" page.

2.2.6. IoT Platform

The IoTP allowed the operating status and feeding data from multiple production lines, units, and farms to be gathered from the ESFs and enabled terminal devices (smart phone and computers) to browse these data remotely. The IoTP ran on the Alibaba ecs.n4.small cloud server, which had a single-core VCPU, 2 GB RAM, 100 GB hard disk, and 0.5 Gb/s network bandwidth.

The IoTP could be divided into three parts: receiving, data, and display layers. The receiving layer was responsible for collecting and parsing the messages uploaded by the central controller, as well as verifying the legitimacy of the data in order to prevent malicious attacks. The data layer stored the ESF operating status and feeding data provided an interface for the display layer to query the data, and also made scientific and appropriate suggestions according to the feeding situation of the sows. The display layer used visualization to enable users to view real-time and historical data, including information relating to the feeding situation, feeding scheme, and the ESF operating status.

The receiving layer was constructed using the Spring Boot backend framework and Java programming language, and data were stored in a MySQL database. The data-browser software in the display layer was built using the Vue frontend framework and JavaScript programming language. Coupling was decreased and scalability advanced because of the separation of the frontend and backend. Figure 7 shows the layered architecture of the IoTP as well as the data-browser software viewed on a smart phone.



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

Figure 7. (**a**) IoTP layered architecture and (**b**) the data-browser software viewed on a smart phone.

2.3. Statistical Analysis

2.3.1. Feed Delivery Accuracy of the Electronic Sow Feeders

The accuracy of ESFs in delivering feed is crucial for ration feeding and preventing feed waste. The relative error is calculated as shown in Equation (1), and the smaller the relative error, the higher the feeding accuracy.

$$\delta = \frac{M - M_0}{M_0} \times 100\% \quad (1)$$

where δ is the relative error; M is the weight of actual feed in g; and M_0 is the weight of expected feed in g.

The coefficient of variation is calculated as shown in Equation (2), and the smaller this is, the better the feeding stability.

$$CV = \frac{S}{X} \times 100\% \quad (2)$$

where CV is the coefficient of variation; S is the sample standard deviation; and X is the mean feed weight.

2.3.2. PDA Communication Reliability

The communication reliability of the PDA had a significant impact on its dependability for controlling ESFs and the motivation of breeders to use a PDA. The reliability of wireless communication between PDA and ESF can be effectively evaluated using the packet loss rate (PLR) and response time (PDA_RT). A smaller PLR indicates more reliable wireless communication, and this is calculated as shown in Equation (3).

$$PLR = \frac{S_a - R_b}{S_a} \times 100\% \quad (3)$$

where Sa is the number of times packet-a was sent and Rb is the number of times packet-b was received.

The shorter the PDA_RT, the more rapid the wireless communication, and this is calculated as shown in Equation (4).

$$PDA_RT = \begin{cases} T_r - T_s, \text{ successfullyreveivepacket} - b \\ \\ 5000 \quad , \text{ losepacket} - b \end{cases} \quad (4)$$

where T_r is the timestamp of packet-a sent by PDA and T_s is the timestamp of packet-b received by PDA.

2.3.3. Data Insertion Performance of the IoT Platform

The IoTP was responsible for maintaining communication with multiple central controllers as well as ensuring data security. In the performance test of the IoTP, throughput rate (TR) and response time (IoTP_RT) were important indicators. TR is calculated as shown in Equation (5) and refers to the number of requests processed per second. A larger TR indicates that the IoTP can connect with a greater number of central controllers.

$$TR = \frac{NoR}{T_c} \quad (5)$$

where NoR is the number of requests processed by the IoTP and T_c is the total time taken to process all requests in ms.

IoTP_RT is calculated as shown in Equation (6) and refers to the time taken to process a request. The smaller the response time, the faster the IoTP processes the request.

$$IoT_RT = T_f - T_s \quad (6)$$

where T_f is the time in ms at which IoTP finishes processing the request and T_s is the time in ms at which the IoTP starts processing the request.

3. Results

3.1. ESF Feed Delivery Experiment

The ESF ration feeding depended on both the speed of feed delivery and the rotation angle of the auger. The speed of feed delivery refers to the mass of feed delivered by a revolution of the motor. The rotation angle of the auger was electronically calculated to feed rations of different sizes. In the gestation unit, the feed was transported via a feed line and

chain, with longer paths resulting in increased abrasion. In order to investigate the effect of abrasion on feeding performance and the stability of the system, the speed of feed delivery was measured using rations of different sizes. The trials were conducted on a sample feed line with 60 consecutive ESFs. The tools included electronic scales (EHA28, Guangdong Xiangshan Weighing Instrument Group Co., Ltd., Zhongshan, China) and containers.

For the speed measurement, a PDA was used to control the 60 ESFs to rotate augers sequentially, and the mass of feed delivered was measured. The error from 30 revolutions was smaller than that from one revolution, so the former was chosen for the speed measurement. The results are shown in Figure 8. The data were essentially centered between 1350 g and 1450 g, with a standard deviation of 21.60, a mean value of 1395 g, and a coefficient of variation of 1.55%. Fifty-seven of the feeders had similar delivery speeds, whereas feeder numbers 5, 31, and 59 deviated further, which could be due to variations in the auger, motor, plastic box, or even the installation environment. The data indicated that there was no obvious relationship between feed abrasion and delivery speed on a feed line, and 60 ESFs had good feeding uniformity.

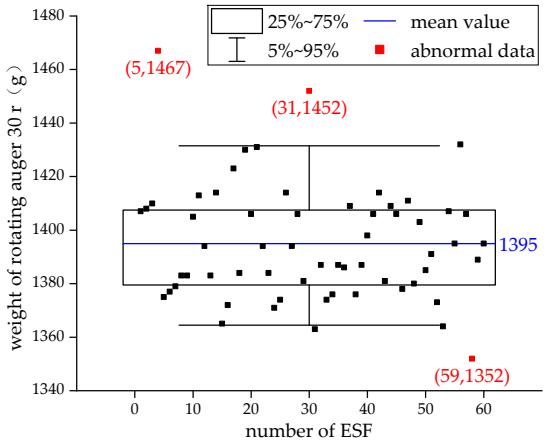
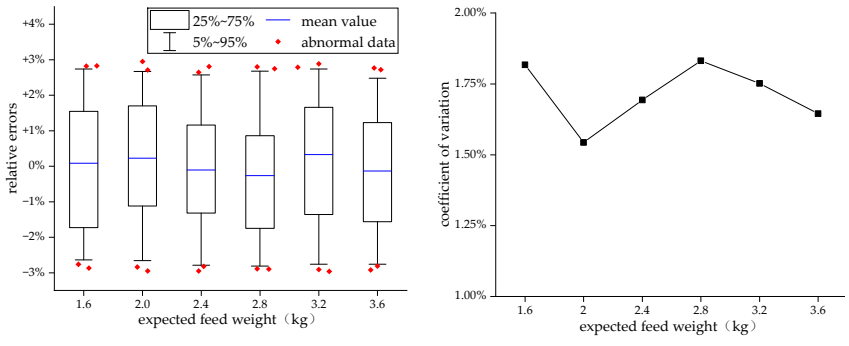


Figure 8. Weight of feed delivered by 60 consecutive ESFs with 30 revolutions of the augers.

For the ration feeding, six experimental groups were established: 1.6 kg, 2.0 kg, 2.4 kg, 2.8 kg, 3.2 kg, and 3.6 kg. In each experimental group, 60 ESFs were controlled to deliver feed quantitatively, and the weight of feed actually delivered was measured separately. The results in Figure 9 show that the relative error of the feeding system consistently remained within ±2.94% and the coefficient of variation was less than 1.84% at different expected feed weights. In terms of overall feeding performance, the feeding system was shown to have a low relative error, a low coefficient of variation, high accuracy, and strong stability, which met the requirements for the accurate control of feed allowances for sows.



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

Figure 9. Relationship between (**a**) the relative error and the expected feed weight and (**b**) the coefficient of variation and the expected feed weight.

3.2. PDA Communication Experiment

The RSSI of the PDA affects its communication ability and can lead to socket pipeline rupture and information loss, in addition to interfering with the normal operation of the feeding system. In order to investigate the relationship between RSSI and PDA_RT, five ESF were randomly selected as samples and divided into eight groups with RSSI as the variable. The test process was as follows: (1) the PDA sent packet-a to the ESF, and recorded the time of sending; (2) the ESF received packet-a and replied with packet-b; (3) the PDA received packet-b and recorded the time of receipt. The number of times packet-a was sent, the number of times packet-b was received, the times at which packet-a was sent, and the times of receipt of packet-b were then counted, and the PLR and PDA_RT calculated.

During the communication request process, to ensure the uniqueness of the packet-b response, the PDA could only run one request at a time. The PDA released the socket channel for other requests only after a complete process was finished. If the PDA sent packet-a but did not receive packet-b, the socket channel could be continuously occupied, causing subsequent communication requests to be blocked. Therefore, the upper limit of the communication duration was set at 5000 ms. If packet-b was not received within 5000 ms, the communication request would be regarded as timed out and terminated.

Figure 10 shows the results. When the RSSI was from −80 dbm to −70 dbm, the PDA sent 146 packet-as and received 141 packet-bs, with a PLR of 3.425%. When RSSI was from −90 dbm to −80 dbm, the PDA sent 47 packet-as and received 32 packet-bs, with a PLR of 31.91%, and the communication pipeline was easy to disconnect, which explained the small sample size at this interval. When the RSSI was from −70 dbm to −10 dbm, there was no packet loss, the average PDA_RT was 556.05 ms, and the communication between the PDA and ESF was stable. Therefore, the power of the ESF WLAN transceiver in the ESF should be adjusted to an RSSI between −70 dbm and −10 dbm to meet the requirements of the application used by the gestation unit.

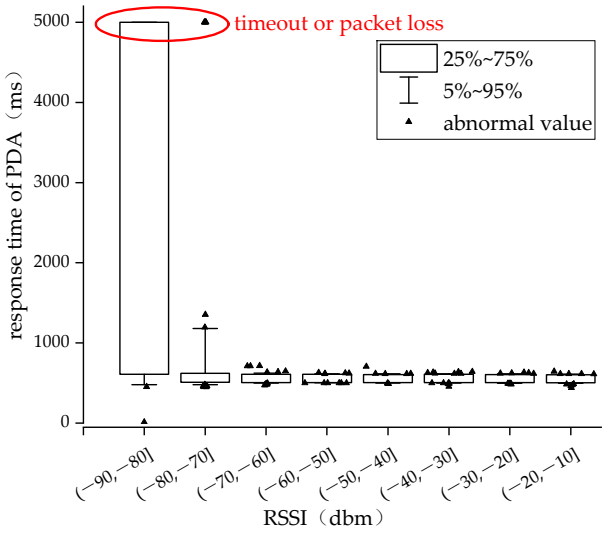


Figure 10. The relationship between PDA_RT and RSSI.

3.3. Data Insertion Experiment for the IoT Platform

The IoTP had to handle multiple concurrent data insertion requests simultaneously, and its performance in data insertion was more critical to the system's reliability than its data reading performance. As the number of central controllers deployed increased, IoTP concurrency also increased, raising the risk of the server encountering issues such as excessive memory usage, inadequate CPU processing power, and blocked IO resources. These problems could eventually result in the service program crashing.

In order to explore the optimum number of concurrent data insertions that the IoTP could load under the existing server configuration, we developed a Web application using

Java programming language and executed it on a Tomcat server. The performance test of the web application running on Tomcat was carried out using the software JMeter 5.6.2. The detailed process was as follows: (1) We established 22 thread groups, each representing a different number of concurrent threads (ranging from 0 to 2200 threads in increments of 100). These thread groups were set up to simulate the task where the Center Controller sent HTTP requests to the IoTP. Each thread simulated a Center Controller. (2) The packet size of each Http request was set as fixed 364 bytes. When IoTP received an HTTP request, it was parsed into a database row structure, and then inserted into the database. The IoTP would respond with a message indicating the successful data insertion. All threads initiated within a span of 5 s. JMeter was used to generate an aggregated report, allowing the analysis of the system's response time and throughput rate.

The experimental results are shown in Figure 11. For concurrent threads below 1700, there was a gradual increase in both the TR and the average IoTP_RT with the escalation of concurrent threads. However, once the concurrent threads exceed 1700, both the TR and average IoTP_RT stabilized at approximately 254 requests per second (rqs) and 4548 ms, respectively. The cause was the server being configured with one virtual cpu core and 2 GB memory. When the number of concurrent threads reached 1700, the resource usage reached the maximum and the request was blocked. This behavior could be attributed to the server configuration, which consisted of a single virtual CPU core and 2 GB of memory. As the concurrent threads reached 1700, resource usage peaked, resulting in blocked requests. Consequently, it was evident that the IoTP experienced a performance bottleneck when the number of concurrent threads exceeded 1700, highlighting the need to avoid overloading it. On the other hand, when the concurrent threads remained below 1700, the IoTP exhibited improved performance and ensured the availability of additional computational resources to handle unforeseen circumstances.

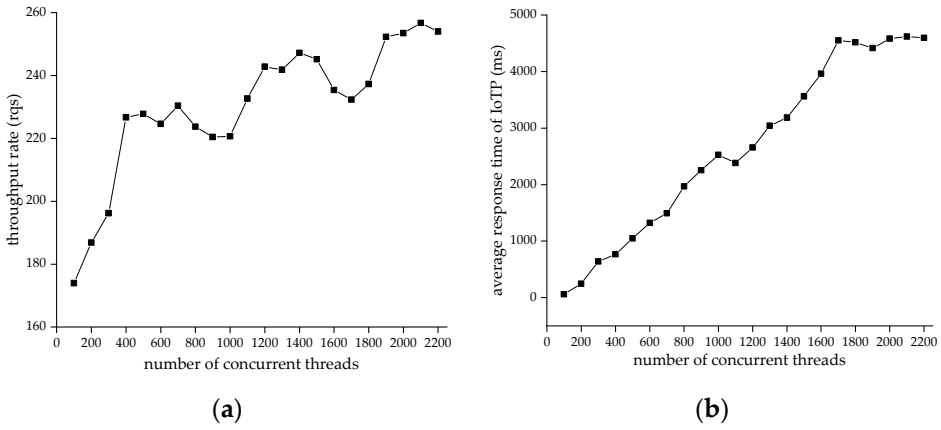


Figure 11. (**a**) Relationship between TR and concurrent threads and (**b**) relationship between average IoT_RT and concurrent threads.

4. Discussion

In Europe, there is increased protection of animal welfare. However, in many developing countries and regions, stalls are still used to raise sows in gestation units. Most studies focus on the design of precision feeding equipment in group housing, but few have considered the problems that need to be overcome for precision feeding in stall housing systems: (1) conventional feeders are prone to over-adjustment leading to large errors in the delivery of feed; (2) there are many feeders installed in the stalls but a lack of efficient hierarchical control; and (3) with high levels of bio-security, the production area and information department are isolated from each other, leading to the slow transfer of production data.

In this research, we conducted a feed delivery experiment using 60 ESFs installed at various positions along the feed transmission line. The speed at which each ESF delivered feed was measured. The data revealed a central tendency between 1350 g and 1450 g, with

an average value of 1395 g and a coefficient of variation at 1.55%. Notably, our analysis did not reveal discernible relationship between feed abrasion and delivery speed. To evaluate the accuracy of feed delivery, we based our calculations on an average speed of 1395 g per 30 revolutions, and we investigated the relative error between the actual delivered feed mass and the expected delivery mass. Our findings consistently demonstrated that the relative error for all 60 ESFs remained within the range of $\pm$2.94%, with a coefficient of variation of less than 1.84% across different expected feed weights. It is worth noting that Chen et al. [43] conducted a similar experiment, but their focus was on a single ESF, resulting in a maximum relative error of +2%. Given our emphasis on the collective performance of multiple ESFs, the $\pm$2.94% range is deemed an acceptable indicator. The structure of the feeding auger stands out as the optimal choice for the widespread implementation of ESFs, as it ensures uniform and consistent feeding performance.

In the scientific literature, there is a conspicuous absence of data communication of ESFs in large-scale gestation units using stalls. In a study involving the use of the feeding station Nedap Velos, conducted by Thomas et al. [44], a significant challenge arose—feed intake data had to be manually extracted on a daily basis due to the lack of long-term data storage capabilities. Additionally, the study reported instances of lost RFID tags in group housing, resulting in potential inaccuracies in data recording. In our system, each ESF is dedicated to a specific sow, which addressed the issues mentioned above. Furthermore, through the CAN, ESF data are seamlessly transmitted to the Center Controller, facilitating efficient data collection and distribution. This not only enhances data management but also leads to significant cost savings in terms of labor.

Sow production management can be categorized into two approaches: normal management and batch flow management [45]. In batch flow management, timed artificial insemination and the administration of various hormones are employed to regulate the timing of estrus, ovulation, and farrowing [46]. However, normal management necessitates individualized care for each sow. To facilitate this, we designed the PDA for the convenient adjustment of individual ESFs. The PDA features an intuitive user interface that provides essential functionalities for pig farming, effectively reducing the cognitive burden on breeders by minimizing comprehension costs. Through a wired connection with ESFs, close contact between breeders and ESFs is prohibited to ensure bio-safety. In practical applications, maintaining the power of the ESF's WIFI module at levels greater than -70 dbm within an appropriate operating distance is advisable to ensure a stable communication effect.

IoTP was implemented to integrate data from various regions and dismantle information barriers among departments. A server (equipped with one core VCPU and 2 GB of RAM) can manage up to 1700 concurrent threads. Exceeding this limit may result in slow data links, blockages, and, in severe cases, cloud service crashes. To address this, we recommend scaling the number of servers and implementing load balancing algorithms when surpassing 1700 concurrent threads. This approach will enhance system concurrency and fault tolerance. Additionally, considering varying GRPS signal strengths in different pig farms, utilizing Ethernet cables is a viable option to improve the central controller's network signal.

While the system has been successfully implemented on a pig farm in Sichuan Province, China, it proved to be challenging to collect additional data and analyze the feeding status of the sows due to strict access policies aimed at preventing African swine fever. In practice, individuals not directly associated with the pig farm are restricted from prolonged stays or even entry.

In the next stage of our research, we will investigate the effects of this feeding system on the performance of gestating sows and explore the potential associations between gestation days, feed intake, backfat thickness, fetal abortion, litter size, and weaning performance. Furthermore, our team's endeavors may revolve around leveraging IoT platforms along with Big Data analytics and Foundation Models technology, for conducting more comprehensive analyses of production data.

5. Conclusions

In order to achieve precision feeding in gestation units using stalls, and to enhance the management ability of feeding systems, this paper presents a precision feeding system with multilevel control. The three-level hierarchical control method was introduced: (1) CAN-based LAN was employed to unite the Center Controller and all ESFs within a gestation unit, ensuring reliable connections and consistent data; (2) WIFI-based LAN was utilized to establish a connection between an individual ESF and a PDA, optimizing the human–computer interaction experience; (3) the internet was leveraged for real-time sharing of production data between the Center Controller and the IoTP. In the context of the intensification and isolation of pig farms in China, our research enables the automatic adjustment of feed allowance during various stages of a sow's reproductive cycle. This approach may achieve a better balance between feed costs and productive performance, potentially contributing to addressing global food crises. Furthermore, our research dismantles information barriers within the farm, allowing breeders to concentrate on essential tasks such as breeding, vaccination, estrus detection, and more, rather than being burdened with data collection, compilation, consolidation, and distribution.

Author Contributions: J.X. (Jingjing Xia): conceptualization, methodology, software, supervision, and resources; J.X. (Jichen Xu): writing—original draft, writing—review and editing, conceptualization, methodology, investigation, data curation, software, formal analysis, and validation; Z.Z.: writing—review and editing, supervision, conceptualization, resources, and funding acquisition; E.L.: investigation, formal analysis, resources, conceptualization, and funding acquisition; F.W.: conceptualization, methodology, software, and validation; X.H.: data curation, investigation, methodology, validation, and software. Z.L.: data curation, supervision, and resources. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Guangzhou Key Research and Development Project (2023B03J 1363), Special Fund for Rural Revitalization Strategy of Guangdong (2023TS-3), Key Laboratory of Modern Agricultural Intelligent Equipment in South China, Ministry of Agriculture and Rural Affairs, China (HNZJ202209), Guangzhou Basic and Applied Research Project (2023A04J0752), Independent Research Project of Maoming Laboratory (2021ZZ003, 2021TDQD002), and Subproject of National Key Research and Development (2018YFD0701002-2).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We are grateful for the administrative support from the South China Agricultural University and the generous help from the staff working in the pig unit.

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

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