RESEARCH ON REMOTE OPERATIONAL CONDITION MONITORING SYSTEM FOR FULLY AUTOMATIC RICE SEEDLING TRAY LIFTING MACHINES

/

水稻全自动硬质秧盘起盘机远程工况监测系统研究

Chuan-yu WANG¹⁾, Shu-juan YI*¹⁾, Yi-fei LI¹,²⁾, Song WANG¹⁾, Shi-han YANG¹⁾
¹⁾ College of Engineering, Heilongjiang Bayi Agricultural University, Daqing / P. R. China
²⁾ College of Engineering, Northeast Agricultural University, Harbin / P. R. China
Tel: +86-459-13836961877; E-mail: yishujuan@byau.edu.cn;
Corresponding author: Shu-juan Yi

DOI: https://doi.org/10.35633/inmateh-78-34

Keywords: *Rice; Transplanter; Tray Lifting Machines; DTU; Cloud Platform*

ABSTRACT

To enhance the mechanization and intelligence of rice seedling cultivation, this study addresses the problems of high labor intensity, low efficiency, and difficulties in on-site monitoring associated with manual tray lifting machines. A remote operational monitoring system for fully automated rigid tray lifting machines based on wireless communication technology was designed and implemented. The system adopts a Browser/Server (B/S) architecture to establish a cloud-based monitoring platform, including the design of a front-end data visualization interface, the development of back-end data processing and storage solutions, and the definition of the monitoring data structure. The platform integrates functions such as chuck alarm monitoring, rice seedling tray counting, and motor status monitoring. It relies on Programmable Logic Controller (PLC) and Data Transfer Unit (DTU) modules to achieve real-time collection and transmission of operational information. Field experiments conducted in three seedling nurseries in Heilongjiang Province, China, showed that the communication data reception rate consistently exceeded 94.87%, reaching a maximum of 100%. The reception probability of chuck alarm information reached 100%, with an average response time of approximately 0.21 s. The system operated stably without causing damage to the rice seedling trays. The results indicate that the proposed system demonstrates excellent stability and real-time performance in agricultural production environments, providing effective technical support for the promotion and application of intelligent rice seedling cultivation equipment.

摘要

为提升水稻育秧机械化与智能化水平，针对人工起盘劳动强度大、效率低及现场监测困难等问题，本文设计并实现了一种基于无线通信技术的水稻全自动硬质秧盘起盘机远程工况监测系统。系统采用 B/S 架构构建云端监测平台，完成前端数据可视化界面设计、后端数据处理与存储方案构建，并定义监测数据结构。平台集成卡盘报警、起盘量监测及电机状态监测功能，依托 PLC 与 DTU 模块实现工况信息的实时采集与上报。在黑龙江省三处育秧棚内开展实地试验，结果显示通信数据接收率均超过 94.87%，最高达到 100%；卡盘报警信息接收概率为 100%，平均响应时间约 0.21 s，系统运行稳定且未造成秧盘损坏。研究表明，该系统在农业生产环境中具备良好的稳定性与实时性，可为智能化水稻育秧装备的推广应用提供有效技术支撑。

INTRODUCTION

Currently, China's rice cultivation area has exceeded 4.34 million mu, with an annual output of approximately 2.07 million tons *(Cui et al., 2017)*. Some regions in China have begun using the stacked tray darkroom technique to cultivate rice seedlings *(Han, 2024)*. Compared to traditional rice seedling cultivation methods, this technology can reduce seed usage by 10% to 15% and advance seedling emergence by 5 to 7 days *(Jia, 2021)*. Manual transplanting during the rice seedling tray lifting phase involves high labor costs, requires a large workforce, and is physically demanding *(Xie et al., 2025; Li et al., 2023)*. To address this, *Yi et al., (2023)* designed a fully automated rigid tray lifting machines for rice seedlings, gradually mechanizing and automating the process of lifting rice seedling trays. However, the temperature and humidity in darkroom rice seedling–raising greenhouses are typically high, and ventilation conditions are poor *(Luo et al., 2025)*. Under such conditions, on-site monitoring of the operating status of rice rigid tray lifting machines becomes difficult.

Therefore, implementing remote wireless monitoring of machine operating conditions using wireless communication technology has become an urgent problem that needs to be addressed.

In the field of agricultural wireless communication research, developed countries such as Europe and the United States predominantly utilize various wireless communication technologies including ZigBee, LoRa, or NB-IoT *(Klaina et al., 2021; Pechlivani et al., 2023; Sonavane et al., 2024)*. These technologies have been widely applied in agricultural monitoring scenarios such as large-scale farm monitoring, tractor condition monitoring, and greenhouse environmental monitoring *(Aliyagoda et al., 2023; Eskandari et al., 2024; Shahab et al., 2024; Reddy et al., 2024)*.

In recent years, Chinese scholars have also applied wireless communication technology in agricultural research. *Cui et al., (2017)*, designed a wireless monitoring system for seedling quality in direct-seeded rice transplanters based on ZigBee technology. By uploading data through router nodes, the system enables multi-point, real-time monitoring of seedling quality. *Zhang et al., (2023)*, proposed a decentralized computing resource service system based on blockchain technology. After conducting performance tests on the remote monitoring system and collecting extensive real-time video footage of agricultural machinery operations, he performed a video query on the operational status of a specific piece of farm equipment. *Zhang et al., (2024)*, conducted an analysis of the identification and processing module for wireless communication signals, which offers valuable insights for enhancing communication quality and efficiency in smart agricultural machinery equipment. *Li et al., (2022)*, designed an intelligent agricultural management system that communicates via 5G network technology. The system compares data information with knowledge databases to trigger alerts, ensuring environmental conditions within the managed area remain stable. *Jia et al., (2021)*, analyzed and summarized the issues with remote control technologies currently used in agriculture, identifying problems and solutions within communication technologies such as ZigBee, WiFi, LoRa, NB-IoT, and 5G. *Liu et al., (2022)*, investigated the propagation characteristics of 2.4 GHz Wi-Fi signals in traditional apple orchards. He established a model conforming to logarithmic path loss for each wireless communication node height and each typical multi-robot formation pattern.

This paper focuses on reducing labour intensity and enhancing the mechanization and automation of rice seedling cultivation. Based on the structure and operational process of fully automatic rice tray lifting machines, the paper designs a remote condition monitoring system for such machines utilizing wireless communication technology. The system collects operational data from the tray lifting machines via wireless communication modules and transmits this information to a remote monitoring terminal. This enables remote condition monitoring of the fully automatic hard disk rice tray lifting machines, including monitoring of the rice seedling tray chuck and tracking of the number of rice seedling trays.

MATERIALS AND METHODS

Overall structure of the rice seedling tray lifting machine

The fully automatic rice tray lifting machine mainly consists of a PLC control system, a hobbing-type shovel tray lifting mechanism, a horizontal tray transfer mechanism, and a vertical tray lifting mechanism. The structural configuration of the machine is illustrated in Figure 1, and the main technical parameters are listed in Table 1.

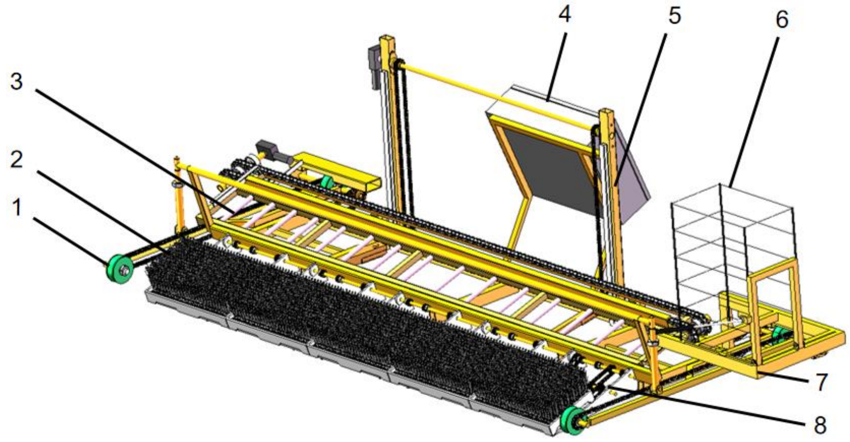

Fig. 1 – Structural diagram of the fully automatic rice seedling tray lifting machine

1.Walking mechanism; 2.Rice seedling tray; 3.Horizontal tray transfer mechanism; 4.PLC control system; 5.Vertical tray lifting mechanism; 6.Rice seedling frame; 7.Rice seedling tray collection area; 8. Tine-tilting hobbing-type shovel tray lifting mechanism

Table 1

Main technical parameters

Parameter	Number
Machine size / (length x width x height) / [mm×mm×mm]	4000×2100×950
Working width / [mm]	3000
Overall machine quality / [kg]	350
Number of cycles in operation / [row]	5
Seedling tray size / (length x width x height) / [mm×mm×mm]	600×300×30

Working principle of the rice seedling tray lifting machine

The tray lifting machine operates in three modes: automatic mode, manual mode, and reset mode. Prior to operation, the running track must be assembled according to the width of the machine, and the height of the tray lifting blade should be adjusted based on the height of the rigid rice seedling trays. After completing these preparations, the PLC control system is activated. The reset knob is then switched to reset mode, initiating the vertical tray lifting mechanism and the horizontal tray transfer mechanism to complete their reset cycles. This procedure ensures stable operation of the machine in automatic mode.

During the tray-lifting phase, the PLC control system activates the DC geared motors of the walking mechanism and the hobbing-type shovel tray-lifting mechanism, driving the machine forward along the track. The lifting shovel is characterized by an angle of 22°, which has been engineered to facilitate the removal of rigid rice seedling trays from the seedbed. Concurrently, the rigid trays are conveyed longitudinally via the toothed conveyor to the lateral tray transfer mechanism. Upon contact with the photoelectric switch, the lateral transfer mechanism is known to undergo a reset to a horizontal position parallel to the ground. The vertical tray lifting mechanism, under the control of the system, adjusts the height of the horizontal tray transfer mechanism to match the pre-set column height of the rice seedling trays. Subsequently, the rice seedling trays are conveyed into the rice seedling frame within the collection area for rice seedling trays by means of horizontal push rods and transport rollers. The tray lifter is capable of simultaneously handling 5 rice seedling trays, with each rice seedling frame having a capacity of 5 trays. The overall process is orchestrated by adjusting the vertical tray lifting mechanism to transfer all trays from the horizontal tray transfer mechanism into the rice seedling frames. The schematic diagram of the working process of the fully automatic rice seedling tray lifting machine is shown in Figure 2.

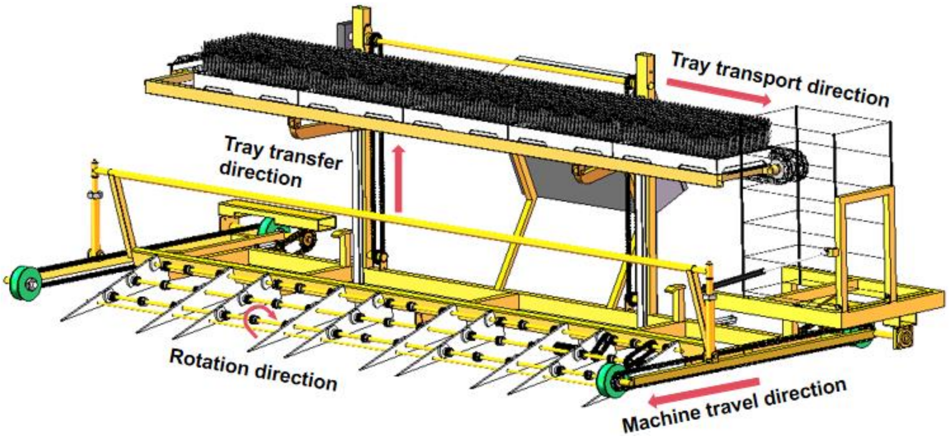

Fig. 2 – Working process of the rice seedling tray lifting machine

Overall system architecture

The architecture of the system under discussion comprises three components: the power supply module, the data acquisition terminal, and the remote monitoring terminal. The data acquisition terminal is controlled by a Siemens S7-200 PLC, which in turn controls a variety of hardware devices.

These include the electric step motor, the hobbing-type shovel-type tray lifting motor, the horizontal tray transfer motor, the vertical lift tray motor, the photoelectric switch, and the speed sensor. The control system interfaces with the DTU via RS485 for the purpose of monitoring data transmission, and interacts with the touchscreen for local operation. The power supply module is responsible for the provision of electricity to the entire data acquisition end. The transmission of data is facilitated wirelessly through the DTU and the wireless transmission module.

The remote monitoring platform is designed to receive data via the wireless reception module, process it through the server, and display it on the human-machine interface for real-time remote monitoring and management. This facilitates efficient monitoring and control of all hardware devices. The schematic diagram of the overall system architecture is shown in Figure 3.

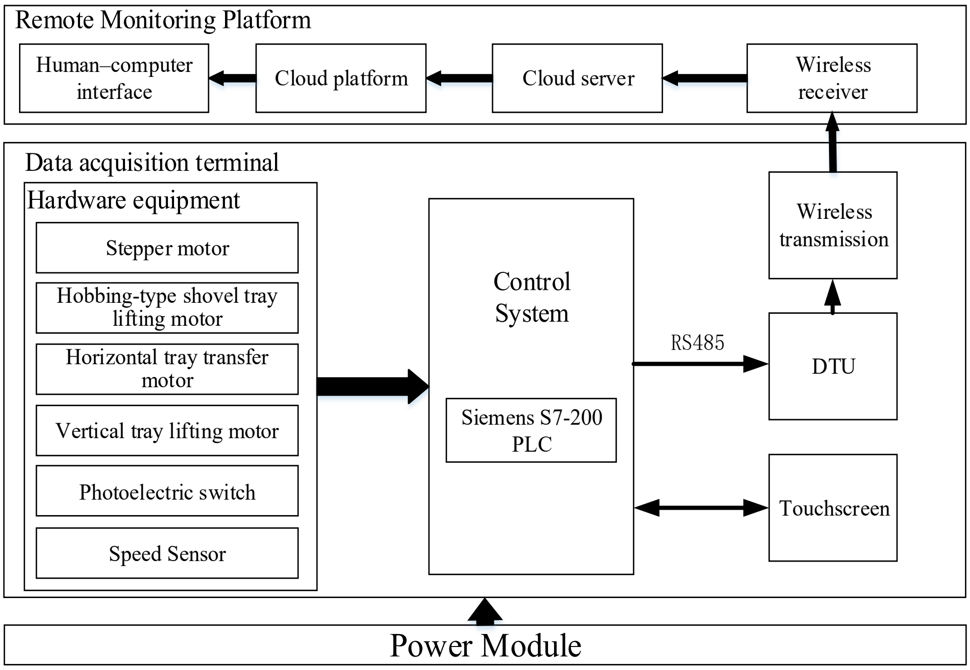

Fig. 3 – Architecture of the wireless remote monitoring system for the rice seedling tray lifting machine

System hardware design

(1) Hardware selection

For the hardware configuration of the tray lifting machine, the PLC used is a Siemens S7-200 CN CPU226, and the touchscreen is a Weintek TK607iP. The walking mechanism is driven by a Unatec MY1016Z-250W motor, while the hobbing-type shovel tray lifting mechanism uses a Zhengfangyu ZFY60-107 motor. The horizontal tray transfer mechanism employs a Yongheng ZYT-104S 300 W motor, and the vertical tray lifting mechanism uses a Yongheng ZYT-90S 500 W motor. The photoelectric switch sensor is LJ18A3-8-Z/BX, and the wireless transmission device is a Youren USR-G780 V2 4G DTU.

The hardware connection diagram of the fully automatic rice seedling tray lifting machine is shown in Figure 4.

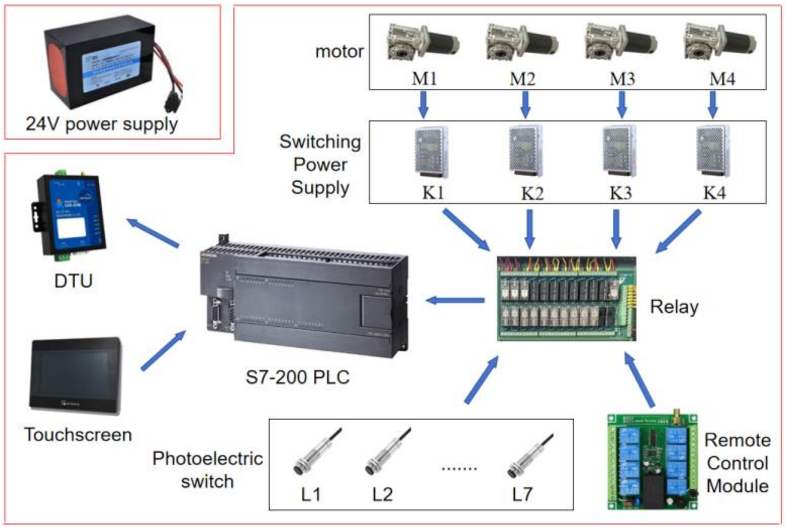

Fig. 4 – Hardware connection diagram

(2) System circuit design

It is evident that, in consideration of the aforementioned hardware selection, the schematic of the PLC circuit was formulated through the utilization of the AutoCAD software.

The fully automated rice tray lifting machine system employs a Siemens S7-200 CPU226 CN PLC as its core, utilizing a modular layout to enable coordinated control of multiple devices. With regard to the power supply, the system utilizes a 24V DC battery with overvoltage protection and filtering circuits. The input ports are connected to a variety of devices, including photoelectric switches, rotary switches, and wireless remote control devices. The output ports interface with four motors and their corresponding relays. The communication ports comprise PORT0, which is connected to a Weinview Co., Ltd touchscreen, and PORT1, which is connected to a DTU data acquisition module. The system circuit diagram is shown in Figure 5.

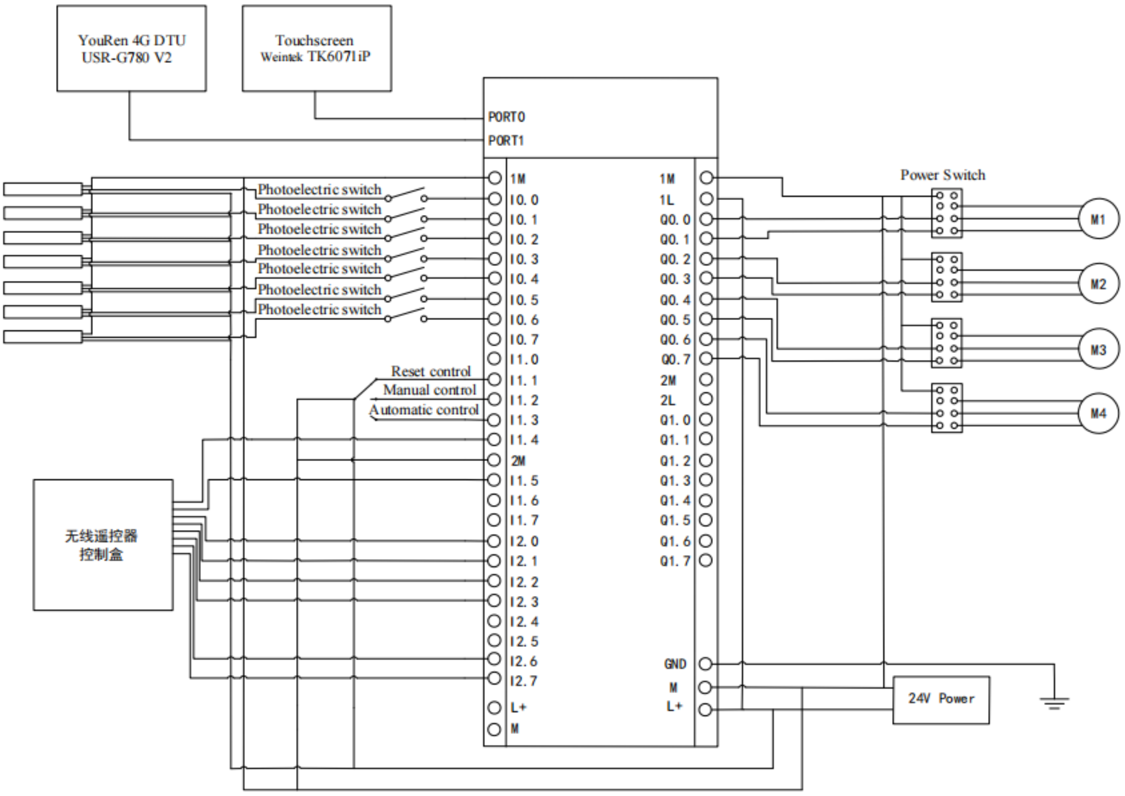

Fig. 5 – System circuit diagram

System software design

(1) Chuck alarm design

The fully automatic rice seedling tray lifting machines incorporate a tooth-pulling design in their tray lifting machines to reduce friction between the trays and the hobbing-type shovel tray lifting mechanism. However, the tray lifting machines have a capacity of 5 trays per row, with each tray measuring 60 cm in width. The width between the shovel tips at both ends of the hobbing-type shovel tray lifting mechanism is 280 centimeters. The total width of five rice seedling trays differs from that of the hobbing-type shovel tray lifting mechanism. In addition, variations in the force application points for each rice seedling tray during gear-driven transport, as well as factors such as soil adhesion to the bottoms of the trays or wear caused by ageing, may lead to uneven movement speeds of the rice seedling trays. This may lead to malfunctions during rice seedling tray lifting operations. Therefore, an alarm mechanism is required to alert operators when such issues occur. The mechanism is integrated into the tray lifting machine to monitor and report abnormal operating conditions.

In the configuration of the chuck alarm design, the tray-lifting mechanisms initiate in automatic mode. A photoelectric switch has been incorporated into the lateral aspect of the hobbing-type shovel tray lifting mechanism, with the purpose of detecting the entry of the rice seedling tray into the device. Upon detection of the tray's entry by the photoelectric switch, the PLC internal timer initiates timing of the lifting mechanism. The hobbing-type shovel-type tray-lifting motor is rotated forward, thereby conveying the rice seedling tray to the horizontal tray transfer mechanism. This process continues until the rice seedling tray makes contact with the rice seedling tray detection photoelectric switch on the horizontal tray transfer mechanism. The process is capable of being completed within 3.4 s without the occurrence of jamming. The configuration of the PLC internal timer to a duration of 4 s is a factor that can be attributed to external factors, including the resistance exhibited by subsequent rice seedling trays and prevailing environmental conditions.

If the photoelectric switch used for rice seedling tray detection on the horizontal tray transfer mechanism fails to detect a tray within 4 s, it indicates that a jam has occurred in the hobbing-type shovel tray lifting mechanism. In the event of a jam, all machine motors are stopped, and the PLC sends a jam signal to the DTU. The DTU then transmits this signal to the operator's monitoring terminal, where the alarm indicator on the monitoring interface flashes to notify the operator of the jam. The configuration of the chuck alarm system is illustrated in Figure 6.

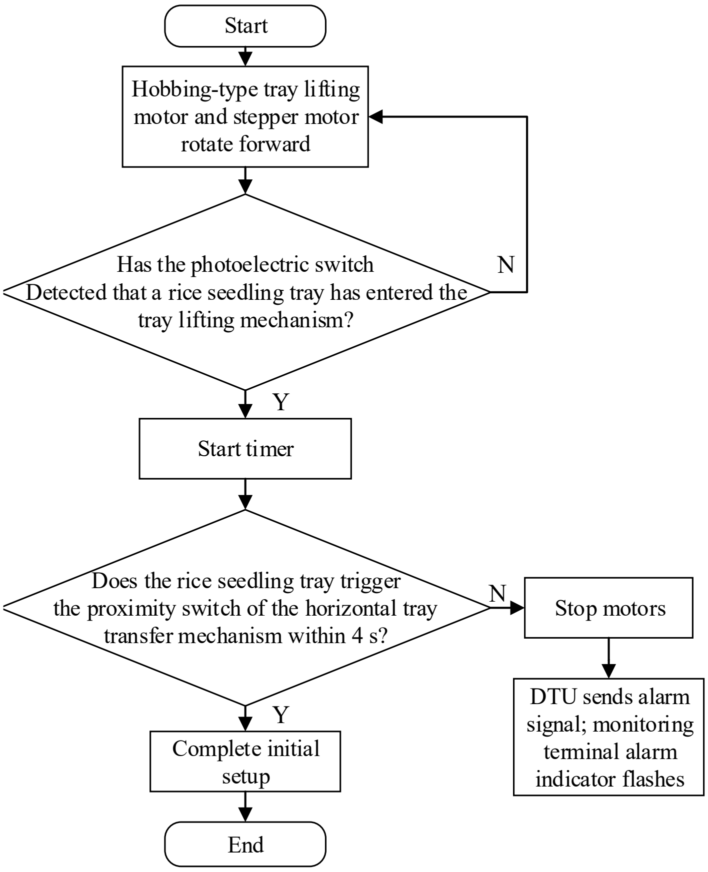

Fig. 6 – Flowchart of the jam detection and alarm control logic for the rice seedling tray lifting machine

(2) Status transmission design for the tray lifting machine

The operating status of the tray lifting machine is primarily determined by the states of four motors: the electric stepper motor, the hobbing-type shovel tray lifting motor, the horizontal tray transfer motor, and the vertical tray lifting motor. The operational state of each motor can be classified as forward rotation, reverse rotation, or stopped. Based on the operating principle of the tray lifting machine and the typical working conditions, a total of 12 different states need to be monitored. In the PLC program, the motor numbers requiring transmission and their corresponding operating states are defined using numerical codes. Specifically, the forward rotation, reverse rotation, and stop states are assigned the values 1, 2, and 0, respectively. Furthermore, the motors are assigned identification numbers in the PLC program: 1 – electric stepper motor; 2 – hobbing-type shovel tray lifting motor; 3 – horizontal tray transfer motor; and 4 – vertical tray lifting motor. The detailed state definitions are presented in Table 2.

Table 2

Transmission Status Definition

Parameter	Assigned value
Electric stepper motor	1
Hobbing-type shovel tray lifting motor	2
Vertical tray lifting motor	3
Horizontal tray transfer motor	4
Motor forward rotation	1
Motor reverse rotation	2
Motor stopped	0

The PLC then transmits the defined status values to the DTU through the free communication port. When the machine enters any of the predefined operating states, the PLC sends the corresponding coded value to the DTU. The DTU subsequently transmits the received data in JSON format to the monitoring platform. Through the cloud service platform, users can view the real-time operating status of the fully automatic rice rigid tray lifting machine, thereby enabling improved monitoring of its operating conditions. The design flow of the status transmission for the tray lifting machine is shown in Figure 7.

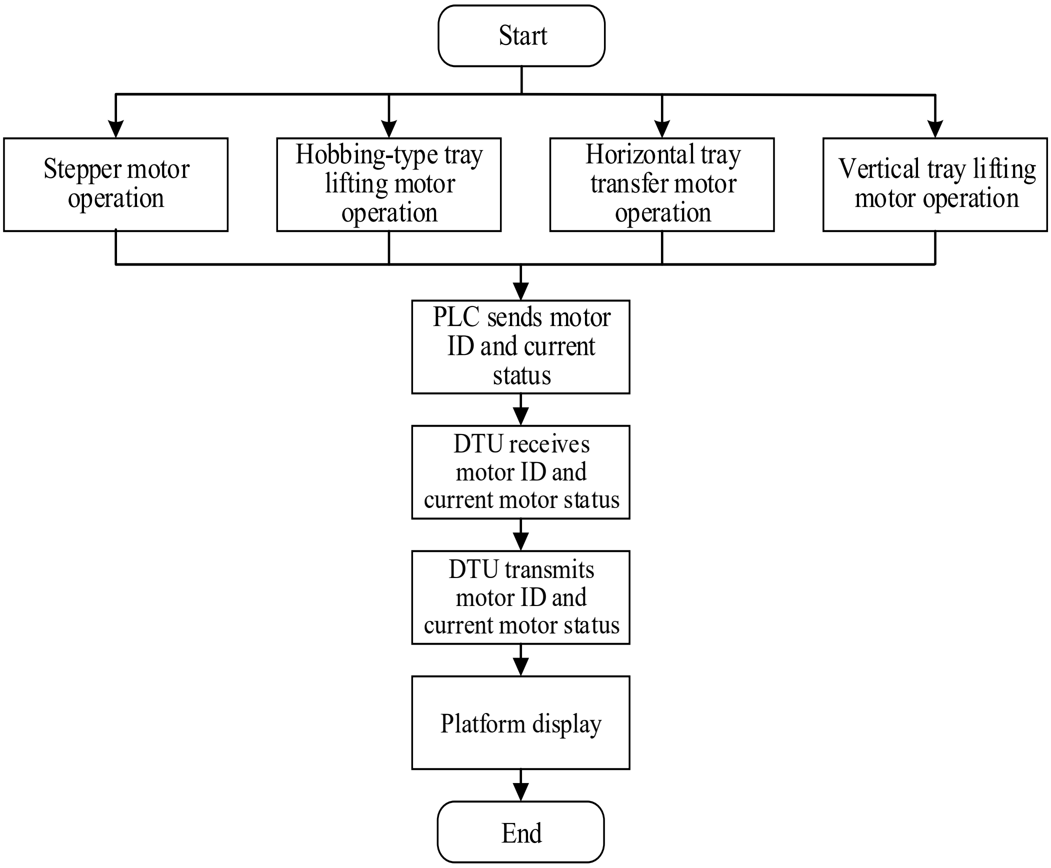

Fig. 7 – Flowchart of the status transmission process for the tray lifting machine

(3) Design of rice seedling tray quantity monitoring

Monitoring the number of rice seedling trays lifted enables the evaluation of the operating efficiency of the tray lifting machine. In this design, a photoelectric switch is installed on the rice seedling frame side of the horizontal tray transfer mechanism to detect the number of trays lifted. When the machine operates in automatic mode, the trays first enter the horizontal tray transfer mechanism and are then transported by the vertical tray lifting mechanism to the upper layer of the rice seedling frame. Subsequently, the push rod of the horizontal tray transfer mechanism pushes the rice seedling trays into the frame. Each time a tray is pushed, the photoelectric switch detects the arrival of the push rod, causing the indicator light of the switch to turn on and the push rod movement to stop momentarily. Since the tray lifting machine can lift 5 rice seedling trays per cycle, the sensor is triggered five times during one lifting cycle, confirming that five trays have been lifted. The total number of lifted trays is recorded until the machine stops operating.

In the PLC program, when the photoelectric switch for rice seedling tray detection is triggered, a signal is generated and transmitted to the DTU, where the signal is assigned a value of 1. The monitoring platform database counts the number of signals transmitted by the DTU, and the accumulated value represents the total number of rice seedling trays lifted during a single operating cycle of the fully automatic rice seedling tray lifting machine. The monitoring process for tray lifting quantity is illustrated in Figure 8.

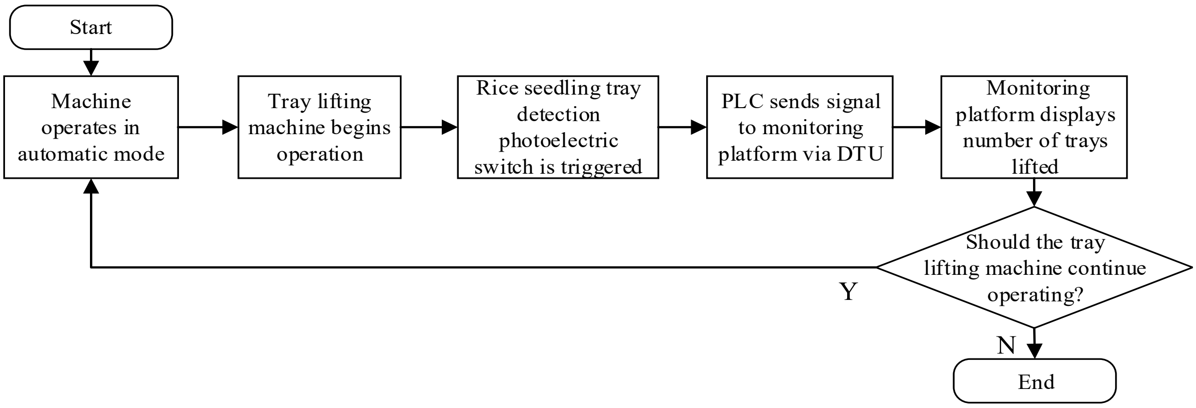

Fig. 8 – Flowchart of the rice seedling tray quantity monitoring process

Overall platform architecture design

The cloud-based service platform designed for the fully automatic rigid rice seedling tray lifting machine adopts a Browser/Server (B/S) architecture implemented through a front-end and back-end separation model. The B/S architecture consists of three main layers: the server layer, which is responsible for centralized system updates and business logic processing; the database layer, which stores the collected data; and the client layer, where the monitoring information is displayed to users through a customized browser interface.

The platform adopts a front-end and back-end separation architecture, with complete functional decoupling between the two components. Secure data exchange between the browser and server is implemented through the HTTP protocol. The front end is developed using the React framework and the Ant Design component library to handle user interface rendering and interaction logic. Data communication between the front end and back end is implemented using the Axios framework together with WebSocket real-time communication channels, with data formatted in JavaScript Object Notation (JSON) to support dynamic updates. The back end is developed using the Python Flask framework to build a microservice-based architecture and is integrated with a MySQL database for data storage and management. This architecture provides reliable data processing and system scalability.

When a user accesses the platform page, the front end first sends a request to the Nginx reverse proxy server. The proxy server retrieves static resources—including HTML, CSS, and JavaScript files—from the Object Storage Service (OSS) server. Based on the requested URL path, the system then forwards an API request to the Flask application server cluster. The Flask server executes the corresponding business logic, retrieves data from the MySQL database according to the request requirements, and finally returns the processed results to the front end in JSON format via the HTTP protocol. The overall architecture of the monitoring platform is shown in Figure 9.

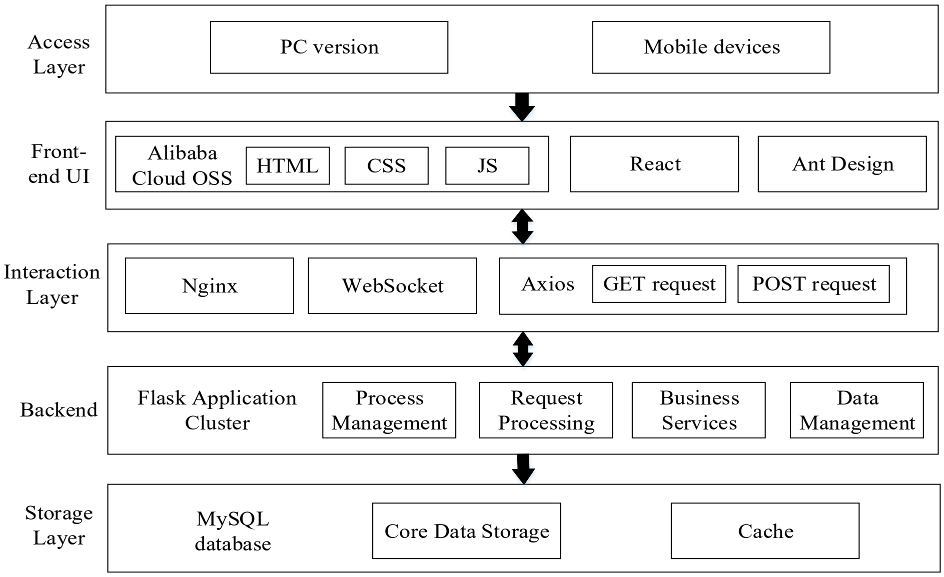

Fig. 9 – Overall architecture of the cloud-based monitoring platform for the rice seedling tray lifting machine

Database design

The cloud-based service platform for the fully automatic tray lifting machine uses a MySQL database to store monitoring data. According to the platform functional requirements and the fundamental principles of database design, the database consists of several tables used to store different types of monitoring information. These include equipment basic information, chuck alarm records, rice seedling tray quantity records, and motor status records.

(1) Equipment basic information

The Equipment Basic Information Table is the primary table used to store operational data during the device initialization stage after power-up. The stored information includes parameters such as power status, operating mode status, data acquisition time, and mode update time. The tray lifting machine and the DTU share a common power supply. After the system is powered on, the DTU sends JSON-formatted data packets to the monitoring platform. The platform parses the received JSON data and displays the current initialization status of the device. The main fields of the equipment basic information table are listed in Table 3.

Table 3

Equipment Basic Field Information Table

Field name	Data Type	Description
deNo	varchar	Unique device identifier
deviec_status	tinyint	Device power-on status
mode	tinyint	Operating mode status
collect_time	datetime	Data collection time
update_time	datetime	Last update time
mode_update_time	datetime	Mode update time
tenant_key	varchar	Tenant identifier

(2) Chuck alarm information

The chuck alarm information table is used to record abnormal operating conditions during rice seedling tray lifting. When a tray jam occurs, the internal timer of the PLC triggers the transmission of a JSON-formatted data packet to the monitoring platform through the DTU. The platform identifies and parses the received data according to the predefined field names. The chuck alarm data packet has the following format: {“deNo”:“M01”,“alerts”:“1”}. The field definitions for the chuck alarm records are listed in Table 4.

Table 4

Equipment Basic Field Information Table

Field name	Data Type	Description
deNo	varchar	Unique device identifier
alerts	tinyint	Alarm status (1 = chuck alarm)
collect_time	datetime	Alarm occurrence time
tenant_key	varchar	Tenant identifier

(3) Number of rice seedling trays collection information

The rice seedling tray quantity collection table is used to record signals triggered by the photoelectric switch during the monitoring of tray lifting quantity. Each time the pusher inserts a rice seedling tray into the rice seedling frame, the photoelectric switch is triggered once. When this occurs, the PLC sends a JSON-formatted data packet to the monitoring platform via the DTU. The data packet has the following format: {“deNo”:“M01”,“number”:“1”}. The field definitions for the tray quantity collection records are listed in Table 5.

Table 5

Number of Rice Seedling Trays Collection Field Information Table

Field name	Data type	Description
deNo	varchar	Unique device identifier
number	tinyint	Tray count event (value = 1 for each detected tray)
collect_time	datetime	Data collection time
tenant_key	varchar	Tenant identifier

(4) Motor status acquisition information

The Motor Status Acquisition Table is used to record the operating status of the four motors in the tray lifting machine. During operation, each motor performs its corresponding action according to the system control logic. The PLC transmits the operating status of each motor to the monitoring platform through the DTU. The motor identification numbers and their corresponding status codes are defined in Table 2. For example, when the electric stepper motor rotates forward, the PLC sends the following JSON-formatted data packet to the platform: {“deNo”:“M01”,“meNo”:“1”,“status”:1}. The field definitions for the motor status acquisition records are listed in Table 6.

Table 6

Motor Status Acquisition Field Information Table

Field name	Data Type	Description
deNo	varchar	Unique device identifier
status	tinyint	Motor operating status
meNo	tinyint	Motor number
collect_time	datetime	Data collection time
tenant_key	varchar	Tenant identifier

RESULTS

Shortest data transmission interval test and results

Under field operating conditions, the minimum time interval between two consecutive state triggers of the tray lifting machine is approximately 0.9 s. To verify whether the DTU can reliably transmit machine status data within this time constraint, a data transmission test was conducted to evaluate the DTU’s ability to receive complete data at different transmission intervals.

In the test, the longest data packet transmitted by the PLC was used as the test sample. The PLC transmitted the forward rotation status of the electric stepper motor of the tray lifting machine in JSON format, with a total data length of 36 bytes. A DTU serial debugging tool was used to monitor and count the transmitted data packets. During the test, data packets were transmitted continuously for 30 s. The transmission interval of the PLC was varied to compare the theoretical number of transmitted bytes with the actual number of received bytes by the DTU. Additionally, it was verified that the received data did not contain garbled characters. The test results are presented in Table 7.

Table 7

Data Transmission Test Results

Transmission interval [s]	Expected bytes	Actual received bytes	Corrupted bytes	Effective bytes	Byte success rate [%]
0.1	10800	5196	4818	378	3.50
0.2	5400	2963	2163	800	14.81
0.3	3600	2657	1275	1382	38.39
0.4	2700	2465	354	2111	78.19
0.5	2160	1994	26	1968	91.11
0.6	1800	1800	0	1800	100
0.8	1350	1350	0	1350	100
1.0	1080	1080	0	1080	100

The experimental results indicate that when the PLC transmission interval exceeds 0.6 s, the DTU achieves 100% data integrity. As the transmission interval decreases, data integrity declines significantly, reaching only 3.50% at an interval of 0.1 s. Therefore, to ensure reliable communication, a transmission interval greater than 0.6 s is recommended. These results demonstrate that the hardware system can reliably support the transmission of all operational status data of the tray lifting machine.

Chuck alarm test and results

To verify the feasibility and accuracy of the chuck alarm function of the tray lifting machine, a simulated rice seedling tray jam test was conducted in a seedling greenhouse.

A total of 15 test trials were performed under different simulated jam conditions, including tray misalignment at different positions, soil adhesion on the tray bottoms, and simultaneous blockage of multiple trays. These conditions were designed to replicate possible failure scenarios encountered in actual production.

During the test, the tray lifting machine was operated in automatic mode. When the photoelectric switch located on the side of the hobbing-type shovel tray lifting mechanism was triggered, the PLC internal timer started counting. If the jam condition persisted for 4 s, the system identified it as a tray jam. Once a jam was detected, all motors were immediately stopped, and the PLC transmitted a chuck alarm signal to the monitoring platform via the DTU. The reception results of the chuck alarm signals are shown in Figure 10.

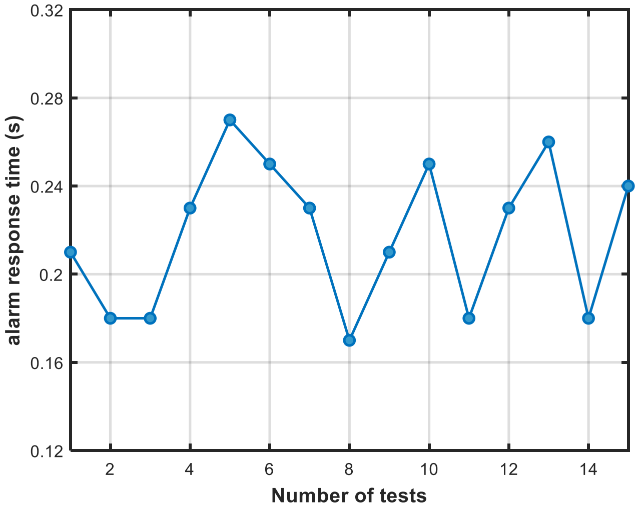

Fig. 10 – Chuck alarm reception test

The experimental results show that, due to wireless communication latency, the average alarm response time of the monitoring platform was approximately 0.21 s. The reception rate of the chuck alarm signals reached 100%, indicating reliable alarm transmission. Minor fluctuations in response time were mainly caused by wireless transmission delays in the greenhouse environment, where high temperature and humidity can increase signal attenuation. However, all delays remained within acceptable limits, and no damage to the rice seedling trays or mechanical wear was observed during the tests. These results confirm that the chuck alarm function of the tray lifting machine meets the system design requirements.

Communication reliability testing and results

The communication equipment and system were tested for reliability at three locations: 859 Farm in Raohe County, Heilongjiang Province; Qixing Farm in Jiamusi City, Heilongjiang Province; and Heilongjiang Bayi Agricultural University in Daqing City, Heilongjiang Province.

Fig. 11 – Communication reliability test of the tray lifting machine

The monitoring platform server was located at Heilongjiang Bayi Agricultural University, with distances of approximately 300 km, 220 km, and 1 km from the three respective test sites. At each test site, the operating tracks and rice seedling trays were arranged in advance. The fully automatic rice seedling tray lifting machine was then used to lift 50 seedling trays under normal operating conditions. During the experiment, the monitoring platform was used to observe the transmission status of the system in real time. The communication reliability test results are presented in Table 6.

Table 6

Communication Reliability Test Results

Test Location	Theoretical Packet Count [Number]	Actual Packets Received [Number]	Successful reception rate [%]
Bawujiu Farm, Raohe County, Heilongjiang Province	195	185	94.87
Qixing Farm, Jiamusi City, Heilongjiang Province	195	189	96.92
Heilongjiang Bayi Agricultural University	195	195	100

The test results indicate that the communication equipment and system achieved a 100% successful reception rate at Heilongjiang Bayi Agricultural University. However, due to the longer transmission distances and weaker signal strength at the farm test sites, slight signal fluctuations were observed during the experiments. The successful reception rate was 96.92% at Qixing Farm and 94.87% at 859 Farm. Despite these variations, all three test locations demonstrated high communication reliability, meeting the requirements for practical applications in agricultural environments. Furthermore, the monitoring platform operated without delays or other abnormalities, ensuring accurate and stable system performance.

CONCLUSIONS

1) A remote operational monitoring platform based on PLC, 4G DTU, and cloud–edge collaboration was developed. The platform enables real-time acquisition of operational data from tray lifting machines in the field, reducing the need for manual inspection and improving information response efficiency.

2) The monitoring system provides a multi-dimensional monitoring scheme for key stages of tray lifting machine operation, including chuck alarm monitoring, rice seedling tray quantity statistics, and equipment operating status monitoring. This approach enables accurate identification of operational states and establishes a closed-loop system for data collection and processing, ensuring the continuity and controllability of rice seedling cultivation operations while providing a data basis for operational scheduling and efficiency analysis.

3) Experiments were conducted to evaluate the minimum transmission interval, chuck alarm response performance, and communication reliability under multiple scenarios. The results show that when the transmission interval exceeds 0.6 s, the system achieves 100% data integrity. The average chuck alarm response time was 0.21 s, with a 100% alarm reception rate, while the communication success rate across different test sites remained above 94.87%. These results demonstrate that the proposed system exhibits high reliability and real-time performance, meeting the requirements for remote monitoring in agricultural production environments.

ACKNOWLEDGEMENT

This study was supported by the National Key Research and Development Plan Project of Heilongjiang Province, China (2023YFD2301604-2).

REFERENCES

[1] Aliyagoda N., Lokuge S, Gunathilake PMPC, Amaratunga KSP, Weerakkody WAP, Bandaranayake PCG, Bandaranayake AU (2023). Internet of Things (IoT) for smart agriculture: Assembling and assessment of a low-cost IoT system for polytunnels. *PLoS ONE*, Vol.18, No.05, United States.

[2] Cui H., Wang T., Zhang B., Xin M., Song Y., Liu C., Ren W., (2017). Design and experiment of rice direct seeding monitoring system based on ZigBee technology (一种基于 ZigBee 技术的水稻直播机播种监测系统设计与试验). *Journal of Shenyang Agricultural University*, Vol.48, No.01, pp. 7–13, Beijing/China.

[3] Eskandari M., Savkin V. A. (2024). Integrating UAVs and RISs in future wireless networks: A review and tutorial on IoTs and vehicular communications. *Future Internet*, Vol.16, No.12, pp. 433, Switzerland.

[4] Han X. (2024). Rice substrate plate darkroom stacked seedling technology (水稻基质板暗室叠盘育秧技术). *Journal of Agricultural Mechanization Research*, Vol.46, No.11, pp. 265–268, Beijing/China.

[5] Jia J., Lu, X., Huang, F., Wang, B., Wang, X., Gao, W., (2021). Analysis and prospects on remote control and wireless communication technology in agriculture (远程控制与无线通信技术在农业中的应用分析与展望). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.52, No.S1, pp. 351–359, Beijing/China.

[6] Klaina H., Guembe I. P., Lopez-Iturri P., Campo-Bescós M. Á., Azpilicueta L., Aghzout O., Alejos A. V., Falcone F., (2021). Analysis of low power wide area network wireless technologies in smart agriculture for large-scale farm monitoring and tractor communications. *Measurement*, Vol.187, United Kingdom.

[7] Li L., Feng J., (2022). Application of 5G network technology in intelligent agricultural management (5G网络技术在农业智能化管理中的应用). *Journal of Agricultural Mechanization Research*, Vol.09, pp. 260-263, Beijing/China.

[8] Li Y. (2021). Application of seedling cultivation technology in dark room with stacked trays (叠盘暗室出苗育秧技术应用). *Northern Rice*, Vol.51, No.06, pp. 42–43, Beijing/China.

[9] Li Y., Liu M., Wang Y., Jiang Q., Yang C., Ge Y., Liu X., (2023). Design and experiment of laser straight-line system for electric soil covering machine (电动摆盘覆土机激光走直系统设计与试验). *Journal of Agricultural Mechanization Research*, Vol.45, No.03, pp. 94–98, Beijing/China.

[10] Liu Z., Liu H., Mao W., Yang F., Wang W., Qin J., (2022). Propagation characteristics of wireless communication signals in traditional apple orchard for multi-robot applications (面向多机器人的传统苹果园无线通信信号传播特性研究). *Transactions of the Chinese Society for Agricultural Machinery*, Vol.53, No.08, pp. 283–293, Beijing/China.

[11] Luo L., Yi S., Li Y., Li B., Chen D., (2025). Design and experiment of PLC-based control system for automatic rice hard tray seedling lifting machine (基于PLC的水稻硬盘育秧全自动起盘机控制系统设计与试验). *Journal of Agricultural Mechanization Research*, Vol.48, No.01, pp. 151–158, Beijing/China.

[12] Min R., Xie Y., Huang W., Hu Z., (2024). Dynamic evolution of high-quality development level of grain production in China: A case study of rice (中国粮食生产高质量发展水平的动态演进——以水稻为例). *Journal of Hubei University of Science and Technology*, Vol.44, No.04, pp. 25–31, Beijing/China.

[13] Pechlivani E.M., Papadimitriou A., Pemas S., Ntinas G., Tzovaras D., (2023). IoT-based agro-toolbox for soil analysis and environmental monitoring. *Micromachines*, Vol.14, No.09, Switzerland.

[14] Qing S. (2024). Research on wireless communication signal recognition based on iterative algorithm (基于迭代算法分析的无线通信信号识别研究). *Journal of Agricultural Mechanization Research*, Vol.46, No.02, pp. 198–202, Beijing/China.

[15] Reddy, S.K., Naik, A.S., & Mandela, G.R. (2023). Development of a Novel Real-Time Environmental Parameters Monitoring System Based on the Internet of Things with LoRa Modules in Underground Mines. *Wireless Personal Communications, 133*, 1517-1546. United States.

[16] Shahab H., Iqbal M., Sohaib A., Khan F. U., Waqas M., (2024). IoT-based agriculture management techniques for sustainable farming: A comprehensive review. *Computers and Electronics in Agriculture*, Vol.220, Netherlands.

[17] Sonavane S. M., Prashantha G. R., Nikam P. D., AVR M., Chauhan J., S., Bavirisetti D. P., (2024). Optimizing QoS and security in agriculture IoT deployments: A bioinspired Q-learning model with customized shards. *Heliyon*, Vol.10, No.02, United Kingdom.

[18] Xie F., Yang J., Fu Z., Liu D., Gong M., Cheng L., (2025). Design and experiment of disk-splitting device of 2BP-2000 rice seedling sowing machine (2BP-2000型水稻育秧播种机分盘装置设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, Vol.40, No.02, pp. 1–11, Hunan/China.

[19] Yi S., Zhang G., Li Y., Li B., Luo L., Wang P., (2023). Design and experiment of a fully automatic plate lifting machine for rice hard disk seedling cultivation. *Agriculture*, Vol.13, No.10, pp. 1–19, Switzerland.

[20] Zhang Y., (2023). Agricultural machinery remote monitoring system based on big data and blockchain technology (基于大数据和区块链技术的农机远程监测系统). *Journal of Agricultural Mechanization Research*, Vol.45, No.09, pp. 197–200, Beijing/China.