PRECISION INTEGRATED DECISION-MAKING AND CONTROL SYSTEM FOR WATER AND FERTILIZER MANAGEMENT IN ORCHARDS BASED ON THE INTERNET OF THINGS AND CLOUD PLATFORM
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基于物联网与云平台的果园水肥一体化精准决策控制系统设计

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ABSTRACT
Addressing the issues of severe resource wastage, low automation levels, and insufficient control precision in traditional orchard water and fertiliser management, this paper proposes a multi-dimensional, collaborative integrated water and fertiliser management system for orchards. This system combines IoT sensing technology, wireless communication technology, cloud platform computing, and intelligent control algorithms. Through a layered architecture design, this system innovatively enhances the perception layer, transmission layer, data layer, and application layer. It integrates diverse communication protocols such as ZigBee, LoRa and NB-IoT, combines sensors for irrigation, fertilisation, and other aspects, and merges intelligent algorithms including PID closed-loop control and fuzzy neural networks. This enables precise water-fertiliser ratio formulation, remote real-time monitoring, and adaptive regulation. Field validation at a demonstration orchard in Guangdong demonstrated water savings of 30%–65%, fertiliser reductions of 40%–50%, and crop yield increases of 20%–135%. Research findings indicate that the deep integration of IoT and cloud platforms significantly enhances water and fertiliser utilisation efficiency in orchards while reducing labour costs. This provides technical support for standardised orchard cultivation, aligning with the demands for precision and intelligent development in modern agriculture.

摘要
针对传统果园水肥管理中资源浪费严重、自动化程度低、管控精度不足等问题，结合物联网感知技术、无线通信技术、云平台计算与智能控制算法，提出一套多维度协同的果园水肥一体化管控体系。该体系通过分层架构设计，分别对感知层、传输层、数据层与应用层进行了改良创新，整合 ZigBee、LoRa 等多元通信协议，集成灌溉，施肥等多方面传感器，融合 PID 闭环控制、模糊神经网络等智能算法，实现水肥精准配比、远程实时监控与自适应调控。通过广东示范果园田间验证，系统可节水 30%~65%、节肥 40%~50%，作物增产 20%~135%，研究结果表明，物联网与云平台的深度融合可显著提升果园水肥利用效率、降低人工成本，为果园标准化栽培提供技术支撑，符合现代农业精细化、智能化发展需求。

INTRODUCTION
China ranks as the world's foremost fruit producer, with orchard cultivation spanning 19.33 million hectares and total fruit output exceeding 261 million tonnes *(Lu et al., 2022)*. However, traditional orchard water and fertiliser management predominantly relies on flood irrigation, furrow irrigation combined with manual fertiliser application *(Singh et al., 2025; Kun et al., 2021; Yang et al., 2025)*, presenting three significant challenges. Firstly, resource utilisation efficiency is low, with an irrigation water use coefficient of merely 0.536 and chemical fertiliser utilisation rates below 40%, significantly trailing developed nations' standards *(Zhang et al., 2025)*. Secondly, labour intensity is high, as manual irrigation and fertilisation in large-scale orchards are time-consuming and labour-intensive, exacerbated by an ageing workforce and labour shortages *(Lin et al., 2020; Zheng et al., 2024; Zhao et al, 2025; Ji et al, 2023; Liu et al, 2025)*. Thirdly, there are pronounced ecological risks, with excessive water and fertiliser leading to environmental issues such as soil acidification, salinisation, nitrate leaching, and groundwater contamination *(Jian et al, 2021; Li et al, 2024; Song et al, 2025)*.

As agricultural supply-side reforms advance, the "one control, two reductions" strategy has become a core objective for green agricultural development, rendering traditional water and fertiliser management models inadequate for meeting the demands of high-quality industrial development *(Zhu et al, 2023; Tran et al, 2023)*.

As a core precision agriculture technology, water-fertiliser integration delivers water and nutrients directly to root zones in precise, crop-specific ratios. This significantly enhances water and fertiliser utilisation rates, reduces environmental pollution, and improves crop yield and quality *(Fu et al., 2021; Wongchai et al., 2022; Adamo et al., 2025)*.

Overseas adoption of water-fertiliser integration commenced earlier, with Israel, the United States, and the Netherlands achieving large-scale implementation. Over 90% of Israeli agricultural production employs integrated water-fertiliser management (*Meng et al., 2022*); 33% of American fruit tree cultivation utilises this technology, forming a variable fertilisation system based on GPS navigation and prescription maps; while the Netherlands has achieved synergistic optimisation of water-fertiliser coupling and environmental control in protected orchards *(Nie et al., 2023; An et al., 2022; Sun et al., 2025)*. These systems exhibit high water and fertiliser utilisation rates, significantly reducing labour intensity for farmers. However, their limitations—including weak system integration, single-dimensional control, limited communication range, and lack of cloud-based coordination—make direct application to China's diverse topographical orchards challenging *(Sheng et al., 2023)*.

The emergence of IoT and cloud platform technologies offers novel solutions to these challenges *(Xu et al., 2025)*. Through multi-sensor collaborative sensing, wireless data transmission, and cloud-based data analysis, remote, automated, and precision water and fertiliser management becomes feasible. Moreover, cloud platforms enable unified multi-region control, substantially enhancing large-scale management efficiency *(Xing et al., 2024)*.

This study aims to construct an integrated IoT-cloud platform system for water-fertiliser management tailored to complex orchard environments. It addresses challenges including multi-parameter precision sensing with stable long-distance transmission, intelligent decision-making and adaptive regulation of water-fertiliser ratios, and cloud-based collaborative control with multi-terminal user-friendly operation. Adaptable to diverse orchard scenarios—mountainous, protected, and large-scale contiguous plots—this system provides a comprehensive technical solution for intelligent water-fertiliser management, holding significant potential for widespread application. The proposed orchard water-fertiliser integration control system design integrates IoT and cloud platform technologies, achieving precision, remote operation, and automation in water-fertiliser management. Research findings indicate that this system significantly enhances water-fertiliser utilisation efficiency, reduces labour costs, increases crop yield and quality, and is adaptable to diverse complex orchard environments. It holds considerable significance for advancing the intelligent and green development of modern agriculture.

MATERIALS AND METHODS

Precision decision control system

System design proposal

Design of a precision decision control system for water and fertiliser application in field crops this system employs a dual-layer architecture comprising a local head-end control system and a remote intelligent cloud platform. The head-end control system serves as the central hub managing multiple devices, undertaking tasks including water extraction, filtration, fertiliser injection, water distribution, and associated controls. It enables real-time control and operational status monitoring of critical components such as water sources, pumps, filters, motors, and electrical control cabinets. It continuously monitors and alerts on critical metrics such as outlet pressure and flow rate of the main pipeline network, filter differential pressure, and three-phase electrical parameters of pump motors. This ensures equipment safety by protecting pumps, motors, filters, and pipelines during system malfunctions.

Addressing the varying water and fertiliser requirements of different fruit tree varieties and growth stages throughout their lifecycle, the orchard water and fertiliser precision control system employs a closed-loop control method combining servo drive with state feedback. It receives prescription data issued by the remote cloud platform in real time, parses it, and transmits valve start/stop control signals to the valve control system. By executing actions such as valve opening, closing, or partial opening, it achieves automated management for the precise application of water, fertiliser, and pesticides. The variable irrigation and fertilisation ratio decision model, constructed based on knowledge engineering theory, is embedded within the integrated water and fertiliser system to achieve intelligent dynamic adjustment of water and fertiliser ratios. The system dynamically adjusts pump group operation based on real-time orchard conditions, comprehensively optimising field moisture ratios and enhancing water resource utilisation efficiency through refined management. Closed-loop control automatically activates solenoid valve operation triggered by prescription decisions from the cloud platform, establishing a precision decision-making framework based on prescription map data and real-time field parameters. This ensures irrigation operations automatically cease at the time points specified in the prescription map.

Primary controller

As the control core of the entire water-fertiliser integration system, the head controller possesses bidirectional data interaction and control capabilities. Downstream, it connects wirelessly via IoT to various monitoring nodes including valve controllers, pump station controllers, and data loggers. Through these nodes, it collects data such as pipeline valve status, pipe pressure, and pump operating parameters. Based on this collected data, it executes control commands including solenoid valve opening/closing, pump start/stop, and variable frequency regulation to achieve precise application of water, fertiliser, and pesticides. Upstream, it communicates with the cloud platform for data storage, processing, and remote intelligent control.

The head unit serves as the operational vehicle for the water-fertiliser integration system. It comprises core components including an irrigation tank, chemical application tank, fertiliser tank, pipeline booster pump, filter, integrated water-fertiliser tank assembly, automatic water-fertiliser application controller, differential pressure butterfly valve, solenoid valves, and flow meters. Its fundamental structure is illustrated in Figure 1.

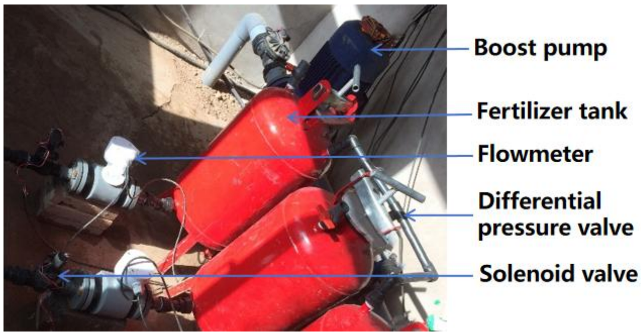

Fig. 1 - Primary equipment configuration plan

The primary controller also incorporates intelligent gateway functionality, establishing communication links between the control system and remote cloud servers via its RTU communication module. This facilitates bidirectional data exchange and control command transmission between the control system and precision management platform, ensuring effective remote command execution and real-time field data uploads. It employs IoT communication protocols such as ZigBee, LoRa, or custom 433 MHz for field monitoring nodes, delivering stable IoT connectivity. Whether utilising broadcast or polling communication mechanisms, it ensures uninterrupted communication links and reliable data transmission. Through each monitoring node, it manages the entire process of sensor data collection, transmission, storage, local display, and cloud uploading for parameters including pressure, flow rate, valve status, and pump operation.

The master controller visually presents the communication status of IoT nodes within the control system, core operational parameters, and the working status of actuators such as valves and pump stations through diverse formats including data lists, trend curves, and graphical representations. This provides maintenance personnel with a clear, comprehensive overview of system operations. It features automatic control parameter configuration, enabling manual/automatic mode switching based on preset requirements to flexibly adapt to varying management scenarios. Users may remotely access the precision crop management platform via smartphones, computers, or other smart terminals to operate various control systems.

On-site controller

The on-site controller serves as an IoT node within the control system. It comprises a power management module, IoT communication module, sensor data acquisition module, relay output module, node enclosure, solar panel array, storage battery, and high-gain communication antenna, and is mounted on field node poles.

The controller's input interface employs an RS-485 serial port for connecting various sensors to gather field data. Its output interface utilises relay outputs capable of driving actuators such as solenoid valves and pump station motors, with a pulse voltage of ±12 V when interfacing with solenoid valves.

On-site controllers perform dual functions of data acquisition and control signal output. Depending on monitored objects and control tasks, they are categorised as integrated monitoring controllers, valve controllers, pump station controllers, and various signal acquisition units. When integrated with corresponding control objects, on-site controllers form intelligent terminal devices such as wireless smart electrically controlled valves, wireless smart pump controllers, wireless smart soil moisture monitors, wireless pipeline pressure measurement and control units, and wireless flow monitors.

Variable rate fertiliser application system

Overall technical approach

The variable fertiliser application control system, serving as the core execution module for precision water-fertiliser integration control, comprises five functional units: the host computer control system, microcontroller system, fertiliser hopper detection module, discharge port fertiliser weighing module, and fertiliser discharge motor control module, as illustrated in Figure 2. Its core operational mechanism functions as follows: the microcontroller, serving as the heart of the micro-control system, simultaneously acquires two critical signals—fertiliser weight within the hopper and discharge chute—via an AD acquisition card. This data is then transmitted to the host computer through an RS-232 serial communication link. The host computer integrates the preset prescription chart information with the two feedback signals. Through algorithmic analysis, it derives precise fertiliser blending ratios and application rate parameters. Control commands are then issued to the microcontroller system, which executes the instructions. This system implements coordinated position and speed control of the fertiliser discharge chute motor. By adjusting the chute wheel speed, variable regulation of the fertiliser blending and application process is ultimately achieved.

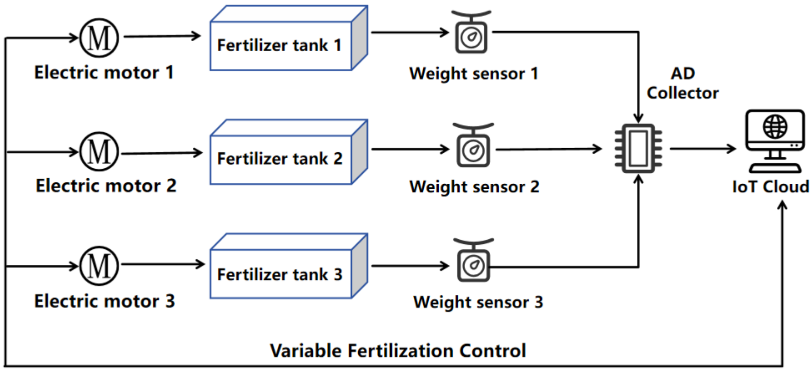

Fig. 2 - Schematic diagram of variable-rate fertiliser application control system

Specific functions of each unit

(1) Host computer control system: Real-time acquisition of fertiliser weight variations within the hopper and feedback signals from the discharge chute via RS-232 serial communication. Integrates prescription maps to precisely match target area fertiliser requirements and blending ratios, generating tailored control commands transmitted to the microcontroller system. This enables coordinated decision-making for variable-rate fertiliser blending and application.

(2) Microcontroller system: Undertakes dual core functions. Firstly, it acquires and pre-processes weight signals from both the hopper and discharge chute, transmitting these via RS-232 serial bus to the host computer. Secondly, based on prescription parameters and vehicle speed signals received from the host, it employs servo control technology to regulate variable fertiliser application throughout the mixing and dispensing process.

(3) Fertiliser hopper detection module: Utilises pressure sensors for real-time monitoring of hopper contents. The process involves: changes in hopper weight causing fluctuations in sensor output signals; the microcontroller system acquiring these voltage variations via an AD acquisition card; signal conditioning followed by transmission to the host computer via RS-232 interface; the host computer calibrating and converting the voltage signals to derive real-time hopper weight changes, representing actual fertiliser application monitoring data.

(4) Discharge outlet fertiliser weighing module: Employing a suspended pressure sensor to perform real-time verification of fertiliser application rates at the discharge outlet. The specific process is as follows: Fertiliser falling from the hopper into the discharge outlet hopper triggers signal changes in the suspended pressure sensor. The microcontroller system acquires this voltage signal via an AD acquisition card and transmits it to the host computer. The host computer processes the data, converting it into the actual weight value of fertiliser at the discharge outlet, thereby forming a closed-loop feedback verification of the fertiliser application rate.

Irrigation control system design

Facility composition

The orchard intelligent irrigation system, serving as a crucial operational component of the precision decision-making control system for water and fertiliser application, comprises core hardware including remote pressure transmitters, remote electromagnetic flow meters, intelligent irrigation controllers, pulse solenoid valves, intelligent irrigation gateways, and a cloud-based decision platform.

The remote pressure gauge collects pipeline pressure signals from the irrigation system, transmitting them via 5G communication to the cloud decision platform. Based on pipeline pressure conditions, the platform assesses system functionality, identifies faults such as leaks, and feeds this information back to the decision control platform. Alarm devices then alert farmers to faults, ensuring timely maintenance. Remote electromagnetic flow meters capture dynamic flow data from orchard irrigation pipelines, transmitting this via 5G to the cloud platform. The platform analyses instantaneous flow rates to assess pipeline operational status and detect leaks, while accumulating flow statistics to quantify water consumption per irrigation cycle across zones. This provides data-driven support for scientific decision-making within the orchard irrigation system.

The cloud decision platform serves as the central brain of the orchard's intelligent drip irrigation system. It collects and stores parameter information transmitted by field irrigation controllers, processes this data to generate precise control commands, and supports the expansion of orchard zone controller units according to user requirements. Concurrently, the cloud decision platform provides 24/7 real-time monitoring, parameter querying, data storage, and analytical capabilities. Its web interface displays orchard, pipeline, and environmental parameters, enabling users to remotely regulate zone solenoid valves via control buttons. All historical parameter data is archived in the server database for user retrieval and download, providing traceability support for irrigation system maintenance and optimisation. Furthermore, the system continuously monitors pump parameters including power consumption, flow rate, and pressure, enabling remote metering control and management of water usage. Through intelligent control technology, pump operation can be regulated to achieve precise flow regulation, thereby conserving water resources.

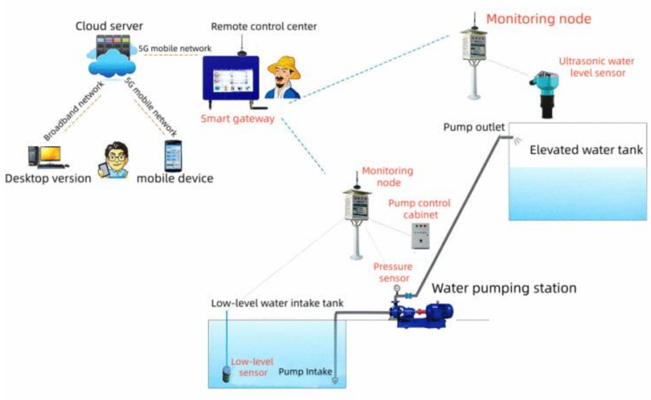

Fig. 3 - Pump station control for irrigation systems

First wireless gateway

The primary wireless gateway serves as the core communication convergence node for the system, primarily facilitating data aggregation and remote transmission for intelligent devices such as pump controllers, wireless valve controllers, and wireless water level sensors, as illustrated in Figure 4. This gateway accesses the internet via GPRS/CDMA/5G mobile communication technology (utilising an IoT SIM card), establishing a direct data exchange link with the cloud-based irrigation management platform. Field intelligent nodes—including pump controllers, valve controllers, soil moisture sensors, and pressure sensors—support two communication access modes: firstly, integrating gateway communication functionality to connect directly with the cloud platform; secondly, forming internal node networking via IoT wireless protocols such as LoRa, with aggregated data subsequently transmitted to the cloud platform via the master gateway. Furthermore, the master gateway may be integrated with the head controller to form an intelligent head controller with gateway functionality. This enables remote real-time monitoring and control of the precision application system for water, fertiliser and pesticides in the field, while reducing system operation and communication costs. The wireless head gateway offers precise, efficient, secure and stable long-range information transmission, alongside advantages of operational simplicity and high signal recognition rates, ensuring the reliability of the system's communication links.

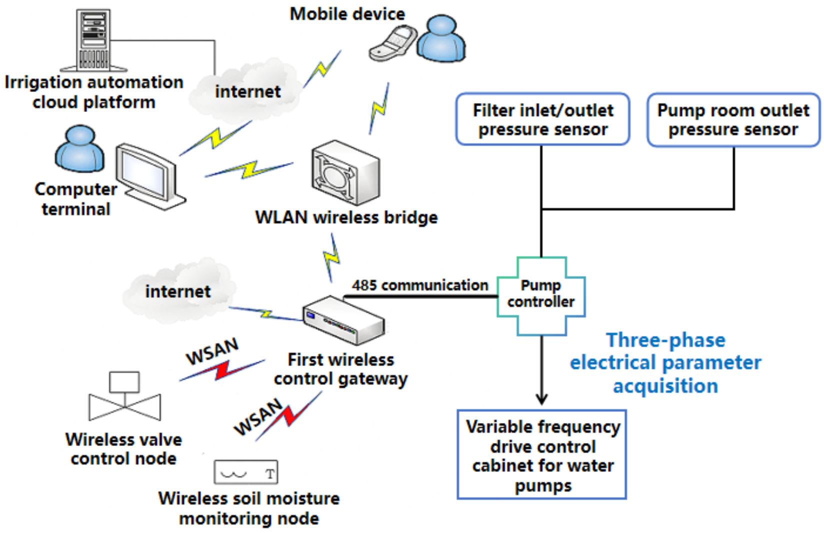

Fig. 4 - First control system architecture diagram

Automated monitoring management

Based on the aforementioned communication architecture, the system enables remote centralised management of pump stations alongside granular monitoring of irrigation water usage and energy efficiency. Total irrigation water consumption is controlled through real-time monitoring and statistical analysis, implementing an authorised water withdrawal control mechanism to provide technical support for managing irrigation water volume within prescribed limits. Real-time energy efficiency monitoring automatically collects electrical parameters such as pump station voltage, current, and power consumption. Combined with operational data including pressure, flow rate, and filter operational status, this enables multi-dimensional statistical analysis. It accurately assesses the rationality of field irrigation patterns, providing foundational data support for optimising water resource allocation and power dispatch.

Users can access comprehensive remote monitoring of pump station operations via cloud-based servers, overcoming spatial (any internet-covered area), temporal (all-hour), and device (compatible with PCs, mobiles, tablets, and other terminals) constraints. Specific monitoring functions include: real-time monitoring of outlet pressure and flow rate, monitoring of variable frequency drive cabinet operational status, and dynamic monitoring of well water levels. The system also features low water level alarms for wells, enabling timely alerts for abnormal water levels to ensure pump station operational safety and continuity of irrigation operations.

Multi-protocol converged communications technology

Internet of Things information transmission

By leveraging a multi-protocol converged communication scheme, perception data collected from the orchard environment is transmitted to the cloud platform with high throughput via 5G cellular networks, where an adaptive protocol selection mechanism is implemented based on the topographical complexity of the orchard: specifically, ZigBee technology is deployed in flat orchard scenarios, which delivers a transmission range of 50-300 m with ultra-low power consumption characteristics and thus is suitable for large-scale sensor node deployment in low-relief terrain, whereas LoRa technology is adopted for mountainous orchard environments featuring complex terrain and long communication distances, enabling an extended communication range of up to 8 km with robust anti-interference capability to mitigate signal attenuation caused by obstacles such as fruit tree canopies and undulating terrain, and the specific configuration and selection criteria of wireless communication modules are elaborated in Table 1.

Table 1

Communication module selection guide

Communication protocol	Core parameters	Suitable scenarios	Model selection
ZigBee	Transmission distance: 50–300 m; Operating current ≤30 mA; Frequency band: 2.4 GHz	Facility orchard/greenhouse	When node spacing is small (< 100 m) and the number of nodes is large (≥50)
LoRa	Transmission distance: 1–8 km; Operating current ≤100mA; Frequency bands: 433/868/915MHz	Mountain orchards/sloping land	Transmission distance > 500 m, complex terrain with numerous obstructions
NB-IoT	Transmission distance: 1–10 km; Operating current ≤20mA; Carriers: China Mobile/China Unicom/China Telecom	Wide-area dispersed orchards (multi-parcel, cross-regional)	When there is no self-built gateway and nodes are dispersed (across townships)

Remote communication mechanism

The remote decision-making control system necessitates the establishment of an effective and reliable remote wireless transmission network. The GSM network's short message service data transmission method has inherent limitations: it suffers from poor real-time performance, is prone to peak congestion during holidays, imposes byte-count restrictions on communication traffic, and carries high tariff costs, rendering it ill-suited for large-volume data transmission requirements. By contrast, GPRS offers distinct advantages: higher data transmission reliability and throughput rates, built upon the Internet Protocol to enable global internet access, permanent connectivity, and pay-as-you-go pricing. This platform utilises the GPRS network as its transmission medium, specifically employing the Transmission Control Protocol within the IP suite for remote data transfer.

The data communication service programme employs multithreading technology to achieve real-time monitoring, reception, and processing of requests sent by the remote data transmission module. This service continuously monitors a predefined port. Upon detecting a request signal from the remote data transmission module, it creates a dedicated thread to process the request. The thread first parses the function code within the request packet, directing it to the appropriate processing workflow based on the function code's specificity. Subsequently, the workflow parses the request data according to predefined communication protocol specifications and completes data persistence by writing it to the database. The communication interaction flow and data transmission link between the server and client are illustrated in Figure 5.

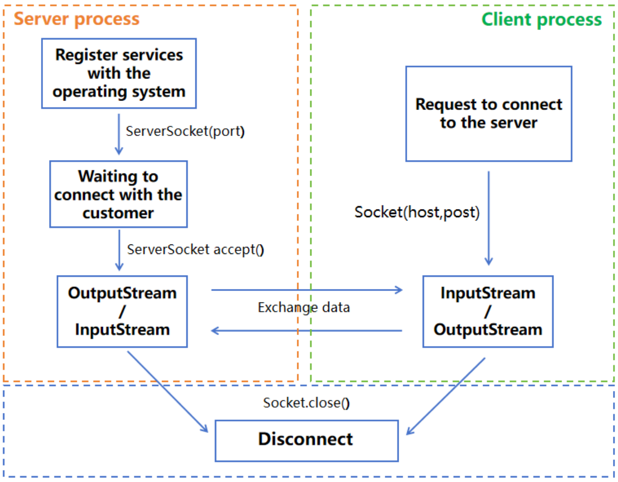

Fig. 5 - Server-client communication process

Cloud platform collaborative control technology

Core architecture of the cloud platform

The cloud platform is built upon the Spring 3.0 MVC framework, employing a MySQL+Redis database architecture to deliver data storage, intelligent decision-making, and remote management capabilities. It provides multi-dimensional analytical reports covering water and fertiliser utilisation efficiency, crop growth trends, and cost-benefit assessments, generating regional water and fertiliser management plans. This enables unified oversight across multiple orchards, with support for data export and visualisation.

Parameters and selection

When selecting hardware for cloud platforms, compatibility should be prioritised to ensure protocol alignment across all component layers. Consideration must also be given to the protection of outdoor components and their environmental adaptability to temperature variations. Wide-temperature models should be selected for cold regions, while anti-condensation models are required for high-humidity areas. Finally, cost and provisions for future scalability must be factored in. Specific selection parameters are detailed in Table 2.

Table 2

Selection criteria for modules of the cloud platform

Core parameters	Technical specifications	Suitable scenarios	Model selection
Data storage	Real-time data storage: ≥100,000 entries; Historical data storage: ≥1 billion entries; Storage type: Relational	Large-scale orchards (≥5 sites)	For long-term data analysis, select "Cloud Server + Local Backup"; For small orchards, consider "Lightweight Cloud" (low cost).
Concurrent access	Supported concurrent users: ≥100; Device connections: ≥1000; Response time: ≤2 seconds	Multi-team collaboration (e.g. growers + technicians)	Cooperatives / Enterprise users should select the “High Concurrency' model”; Individual orchards may opt for the “Basic Edition”.
Security level	Permission Management: Data Encryption for Transmission and Storage; Automatic Backup Frequency: daily	Sensitive data (such as output/cost)	Cross-regional management supports multi-tenant independent administration.
Functional module	Core functions: data monitoring, remote control, alarm management, etc; Extended functions: water-fertiliser models, yield forecasting, energy consumption analysis, etc.	High demand for intelligent solutions	For orchards requiring only basic management controls, the Standard Edition without extended features is available.

Software and system interface design

Control and execution system software

The system software comprises two components: the host computer control software and the microcontroller execution software. The host computer control software reads weight data from the microcontroller and, in conjunction with pre-stored fertiliser application rates for specific plot locations and implement points, calculates the servo motor's rotational speed. It then transmits commands to the microcontroller. Figure 6 illustrates the operational interface of the host computer control software.

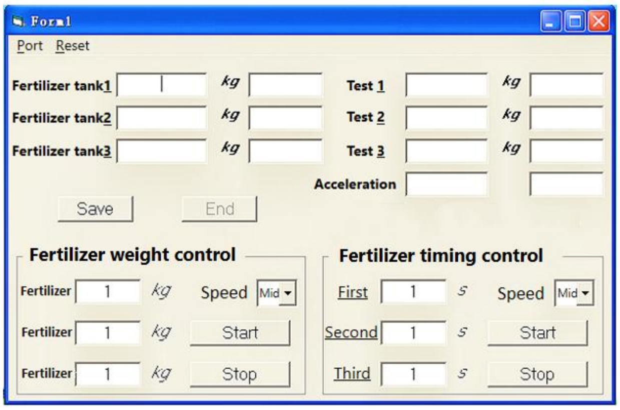

Fig. 6 - Host computer control software operating interface

The specific operational procedure is as follows: click the Port button to access the serial port parameter configuration interface, which includes settings for port number, baud rate, parity bit, data bits, and stop bits. Clicking Reset will clear the fertiliser hopper weight data. Upon system power-up, the host computer software displays real-time weighing values for all three fertiliser hoppers and flow measurements for all three feeders.

Within the fertiliser control panel, pre-set fertiliser quantities for each hopper may be manually input according to operational requirements, or automatically retrieved from the prescription chart by the software. Fertiliser application rate dynamically adjusts in direct correlation with the implement's forward speed: increased forward speed synchronously accelerates fertiliser application, while reduced forward speed correspondingly decelerates it. After completing the above parameter presets, click the "Start" button to initiate fertilisation operations. Data from detection results is saved by clicking the "Save" button. If data saving is unnecessary, clicking the "Cancel" button will prompt a warning dialogue box alerting to the risk of unsaved data. Table 3 summarises the control equipment selection.

Table 3

Control equipment selection table

Controller type	Core technical parameters	Suitable scenarios	Model selection
Edge controller	Interfaces: ≥8 channels; Protection rating: IP65; Power supply: DC 24V	Large-scale orchards (≥10 hectares)	Requirement for basic functionality to be maintained when offline
Local PLC controller	Interfaces: ≥4 channels; Protection rating: IP30; Power supply: AC 220V	Small to medium-sized orchards (≤5 hectares)	When on-site operational requirements are numerous
Industrial touchscreen	Screen size: 7–10 inches; Communication: RS485 / Ethernet; Protection rating: IP65	Local operational requirements (e.g., campus control room)	Supports one-touch start/stop quick operation
Mobile terminal (app)	Functionality: Remote control, data viewing, alert notifications; Communication: 4G/5G/Wi-Fi; Response time: ≤3 seconds	Remote inspection / Multi-orchard management	Multi-site manager selection

The core software module of the microcontroller comprises AD data acquisition and pulse signal output. Upon system power-up or AD7706 reset, the initialisation configuration of the microcontroller's SPI interface is completed first. Data exchange between the microcontroller and AD7706 employs a bidirectional synchronous serial communication method. The AD7706's DIN pin receives control commands issued by the microcontroller, while the converted digital signal is returned to the microcontroller via the DOUT pin. The DRDY register is set to low to receive information from the microcontroller, with the communication frequency set to 2 Mbps. The AD7706 is configured with an update frequency of 50 Hz, yielding a -3 dB cutoff frequency of 13.1 Hz and a gain amplification factor of 1. The microcontroller can output pulses of varying frequencies by configuring the registers of its PWM module. The detailed execution flow of the microcontroller software is illustrated in Figure 7.

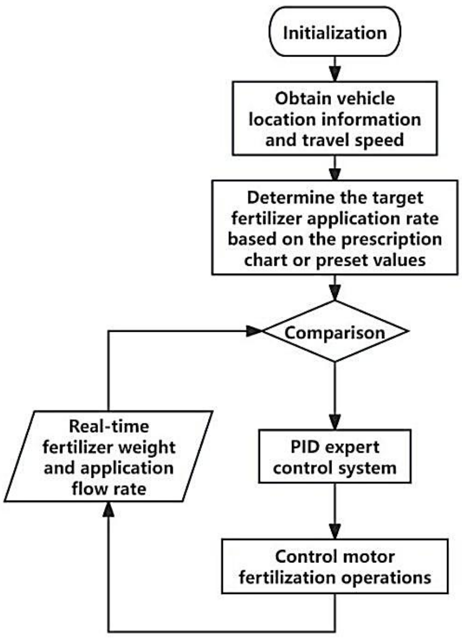

Fig. 7 - Software flowchart

Web application development

The application platform is built upon the Spring MVC framework, with its technical architecture illustrated in Figure 8.

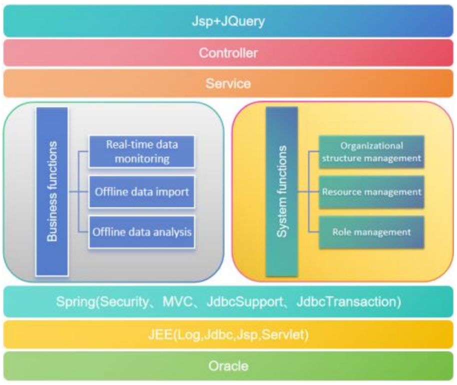

Fig. 8 - Application platform technical architecture

The system employs a Browser/Server architecture for web application development, deployed on cloud server nodes. It supports dual-platform access via mini-programs and mobile applications (Apps), utilising responsive design for multi-device compatibility. The human-machine interface adheres to ergonomic design standards, ensuring excellent usability. Users may monitor core hydrological parameters—including irrigation pressure and flow rates across demonstration zone sub-sections—alongside valve operational statuses in real-time via web browsers or mobile terminals at any location. Concurrently, remote irrigation and fertilisation control commands may be issued to implement time-segmented, zone-specific, and scheduled precision application of water, fertilisers, and pesticides. Historical monitoring data and operational logs can be queried, enabling data-driven analysis for optimising crop irrigation and fertilisation parameters. This design achieves full-process visualised control over irrigation and fertilisation operations, providing data-driven technical support for precision agricultural management decisions. Figure 9 illustrates the zone control interface and display screens for spray flow rates and pipeline pressure within the remote intelligent monitoring system application.

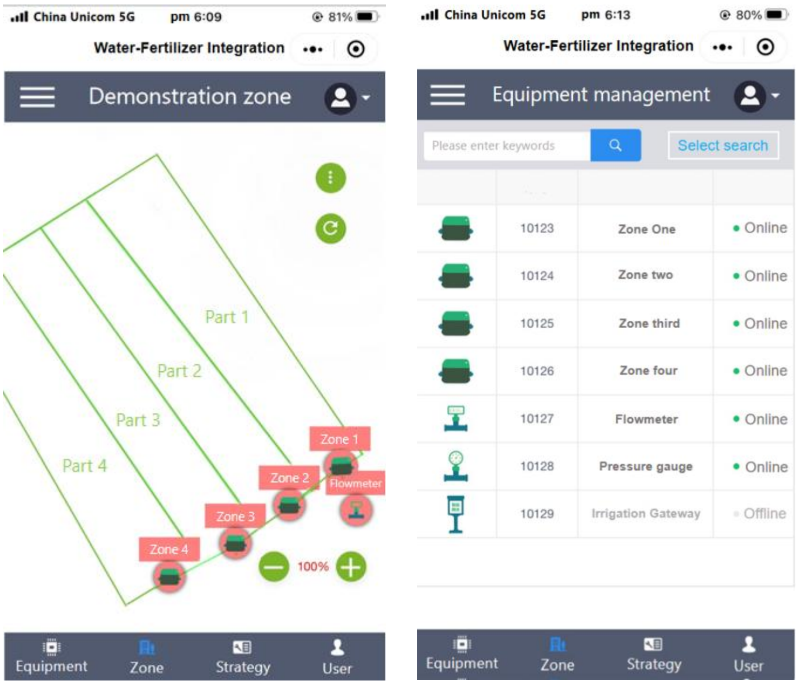

Fig. 9 - Remote intelligent monitoring system App interface

Database selection analysis

As the core repository for system information storage, databases underpin the entire process of data operations including insertion, deletion, modification, and retrieval. Their performance directly determines the overall operational efficiency of the system. Therefore, selecting a suitable database tailored to specific system requirements is crucial for reducing response latency and enhancing overall system performance.

Different database types possess distinct technical characteristics and applicable scenarios, necessitating targeted selection based on the specific application requirements of the monitoring system, as illustrated in Table 4. From the perspective of current market applications, relational databases have long held a dominant position. This category organises data using a two-dimensional tabular structure, achieving efficient CRUD operations through standardised data models and mature algorithmic mechanisms.

Table 4

Database selection comparison

Name	Type	Core features	Applicable scenarios
Oracle Database	Relational	Comprehensive data management capabilities, robust transaction processing power, and a rich product ecosystem	Large-scale enterprise applications
MySQL	Relational	Open-source and free of charge, with outstanding performance, compact size, and cross-platform compatibility	Website development for small and medium-sized enterprises, lightweight applications
SQL Server	Relational	SQL-based, easy to operate, user-friendly management interface, low operational costs	Development of various web projects
NoSQL	Non-relational	Supports dynamic mode, capable of storing semi-structured data, predominantly key-value storage.	High-concurrency, massive-scale data storage scenarios

Taking into account the operational requirements and technical compatibility of this monitoring system, the final configuration has been determined as follows: MySQL 1.8 will be employed to store harvester operational data, whilst Redis will be utilised as a caching database for frequently accessed data. This approach ensures an optimal balance between storage performance and operational demands.

RESULTS

The field trial scene at the citrus orchard demonstration base in Huizhou, Guangdong Province is depicted in Figure 10. Key indicators including citrus fruit growth status and yield were recorded both before and after implementing this water-fertiliser integrated control system. The relevant statistical results are presented in Table 6.

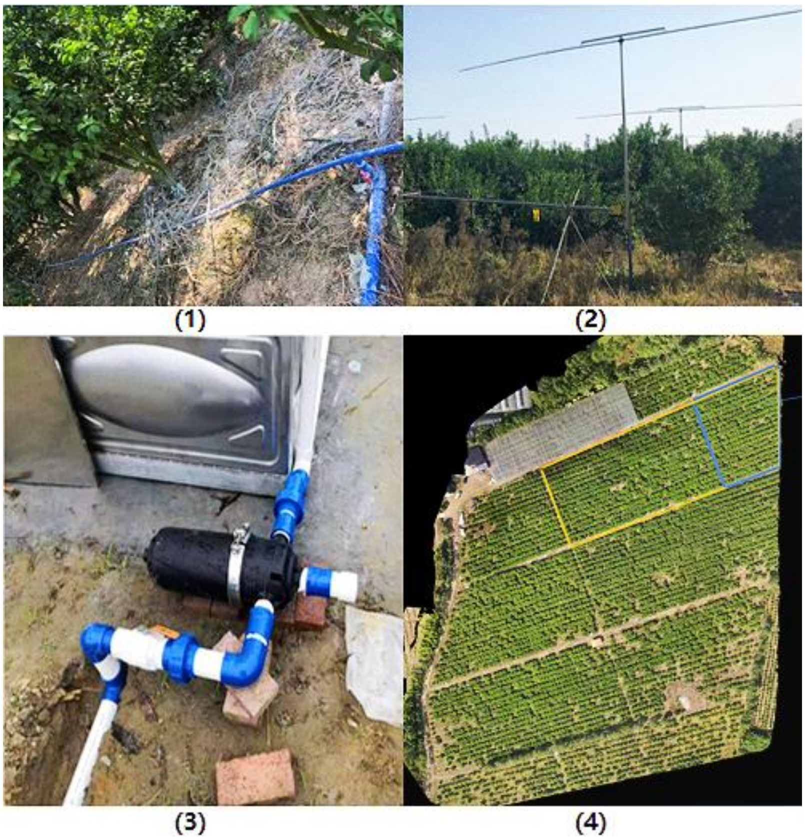

Fig. 9 - Field trial scenario

(1) Drip irrigation pipeline; (2) Dribble board; (3) Fertiliser pipeline; (4) Citrus orchard plot

Table 6

Comparison of citrus growth and yield indicators

Indicator	Experimental group	Control group	Increase rate
Number of fruits per individual tree	445	334	33.2%
Single fruit weight	0.23 kg	0.16 kg	43.8%
High-quality fruit yield	89.1%	70.0%	19.1%
Total output	3180 kg/hm²	2050 kg/hm²	55.1%

The field trial established a precision management system utilising IoT and cloud platforms as the experimental group, with a conventional manual management area serving as the control group. The trial period spanned one year, monitoring indicators including: water and fertiliser use efficiency, crop growth metrics, and system operational stability.

Experimental results demonstrated superior crop growth metrics in the experimental group compared to the control group, indicating that this orchard's integrated water and fertiliser control system effectively enhances fruit quality and yields.

CONCLUSIONS

(1) The system employs irrigation-fertilisation coupling technology, enabling full-growth-cycle requirement design tailored to crop needs. Water and nutrients are delivered directly to crops in precise quantities, at scheduled times, and in proportioned ratios. Statistical analysis and evaluation have been conducted on the selection of all necessary hardware and software components for this process.

(2) The precision control decision system remotely regulates the timing and volume of water and fertiliser application based on crop growth monitoring and detailed prescription information from decision models. It automatically activates and deactivates solenoid valves for unattended operation. Alternatively, by configuring application modes on the controller, the system dynamically applies water, fertiliser, and pesticides according to input instructions.

(3) The precision water and fertiliser decision-making employs the following management methods: operational condition monitoring, closed-loop control, zone management, time-division multiplexing, and platform-based decision-making. This study incorporates a tailored system interface design and optimises the communication network and cloud platform architecture, enabling real-time display of field water and fertiliser status on the remote monitoring interface. Future applications may incorporate multi-source sensor fusion technology combined with machine vision for crop growth monitoring, establishing specialised water and fertiliser models for multiple crops. This would extend applicability to field crops and protected horticulture. Continuous refinement of intelligent algorithms, alongside integration of big data analytics and machine learning, could enable predictive regulation of water and fertiliser requirements, further enhancing the system's adaptability and control precision.

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