Key Technologies and Equipment for Smart Orchard Construction: Prospects and Outlook (Postprint)

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Abstract

Traditional orchard production faces challenges including labor shortages due to population aging, difficulties in managing agricultural machinery and production materials, and low production efficiency. The construction of smart orchards integrating technologies such as the Internet of Things, big data, and equipment intelligence is expected to address these issues. To meet the demands of agricultural modernization in Beijing and lead the development direction of Chinese agriculture, this study established an approximately 30 hm^2 smart orchard for pears and peaches in Xiying Village, Yukou Town, Pinggu District, a key advantageous fruit production area for peaches and pears in Beijing. The orchard deployed over 10 types of information acquisition sensors for diseases, pests, water, fertilizer, and pesticides, and was equipped with 28 types of agricultural machinery supported by mechanized and intelligent technologies. Key technologies adopted include an intelligent information acquisition system, an integrated water-fertilizer management system, and an intelligent pest and disease management system. The intelligent operation equipment system comprises unmanned mowing machines, intelligent anti-freezing machines, trenching and fertilizing machines, autonomous tracked intelligent profiling variable sprayers, six-rotor branch-targeted drones, multi-function harvesting platforms, and pruning machines. Additionally, an intelligent management platform was constructed in the orchard. Comparative analysis revealed that the smart orchard production model can reduce labor costs by over 50%, decrease pesticide usage by 30%–40%, reduce fertilizer consumption by 25%–35%, cut irrigation water usage by 60%–70%, and increase comprehensive economic benefits by 32.5%. The promotion and implementation of smart orchards will further advance fruit industry

production levels in China and foster the development of smart agriculture in the country.

Full Text

Key Technologies and Equipment for Smart Orchard Construction and Prospects

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Abstract: Traditional orchard production faces challenges including labor shortages due to population aging, difficulties in managing agricultural machinery and production materials, and low production efficiency. These issues can be addressed by constructing smart orchards that integrate technologies such as the Internet of Things (IoT), big data, and equipment intelligence. To meet the demands of agricultural modernization in Beijing and guide the development direction of Chinese agriculture, this study constructed a smart orchard covering approximately 30 hectares for pear and peach production in Xiying Village, Yukou Town, Pinggu District—an important high-quality fruit production area in Beijing. The orchard deployed more than ten types of sensors for acquiring information on diseases, pests, water, fertilizers, and pesticides, and was equipped with 28 types of agricultural machinery supported by mechanization and intelligent technologies. Key technologies include an intelligent information acquisition system, an integrated water-fertilizer management system, and an intelligent pest management system. The intelligent operation equipment system comprises unmanned lawn mowers, intelligent anti-freeze machines, trenching and fertilizing machines, autonomous tracked intelligent profiling variable sprayers, six-rotor branch-to-target drones, multi-functional picking platforms, and finishing and pruning machines. Additionally, an intelligent management platform was constructed in the orchard. Comparative analysis revealed that the smart orchard production model can reduce labor costs by over 50%, save pesticide usage by 30%-40%, reduce fertilizer usage by 25%-35%, decrease irrigation water consumption by 60%-70%, and increase comprehensive economic benefits by 32.5%. The promotion and implementation of smart orchards will further advance China' s fruit production level and facilitate the development of smart agriculture in China.

Keywords: smart orchard; Internet of Things; intelligent agricultural equipment system; driverless machinery; smart orchard management platform; information acquisition system; intelligent profiling sprayer

1 Introduction

Traditional orchard production requires substantial manpower and material resources, as well as experienced fruit growers to perform intensive, complex, and laborious management tasks and decision-making. According to surveys and interviews conducted by the author' s team with fruit growers in Xiying Village, Pinggu District, Beijing, the aging of fruit growers is severe, with those over 50 years old accounting for more than 70% of peach growers, most of whom have education levels below junior high school. Orchard production faces labor shortages and rising production costs, with daily wages reaching as high as 500-600 yuan per person per day.

With the advancement and practical application of new technologies such as IoT, big data, artificial intelligence, and 5G, "machine replacement of humans" has gradually become a priority in orchard production. A smart orchard refers to the integration of multiple IoT and electronic information technologies throughout the entire production process to reduce labor input and production costs while achieving precise management of water, fertilizer, and pesticides to improve efficiency and reduce environmental pollution. IoT technology forms the foundation of smart orchards, connecting multiple sensors to the system control platform through IoT and communication networks. By fusing data from various sensors for comprehensive decision-making and establishing two-way communication links using 5G and other communication technologies, the system can distribute operation tasks to intelligent machinery and receive operation status feedback in real time. This enables precise control of inputs such as pesticides and fertilizers and monitoring of mechanization effectiveness, achieving unmanned, efficient, and precise production. Combining blockchain technology with IoT devices to record the entire orchard production process can enable fruit traceability.

Typical smart orchards comprise three main components: information acquisition, historical data storage and decision-making, and execution. The information acquisition component obtains crop, soil, and meteorological information through an "air-space-ground integrated sensor network" consisting of mobile information acquisition robots, remote sensing drones, and fixed ground-based sensors. Information from the entire growing season is stored on backend servers, and decision models are generated through big data and artificial intelligence methods to guide orchard management operations. The data storage and decision-making component aggregates all data and is responsible for network access of all sensors and intelligent machinery, often employing high-availability technologies such as multi-machine redundancy to ensure system reliability. The execution component includes various intelligent operation machines, such as plant protection drones, intelligent lawn mowers, intelligent sprayers, pruning and fertilizing equipment, integrated water-fertilizer systems, and picking robots. Through the orchard management platform, operation tasks can be assigned to machinery while real-time operation status parameters are transmitted back to enable remote monitoring.

The smart orchard demonstration site in this study is located in Xiying Village, Yukou Town, Pinggu District, Beijing, including a 10-hectare peach orchard (40.1920°N, 116.9870°E, approximately 150 mu) and a 20-hectare pear orchard (40.1951°N, 116.9835°E, approximately 300 mu). The planting row spacing is 4 m with plant spacing of 1.5 m, as shown in Figure 1 [Figure 1: see original paper]. Standardized planting facilitates mechanized operations. The Pinggu smart orchard deployed more than ten types of sensors for diseases, pests, water, fertilizer, and pesticides, and was equipped with 28 types of agricultural machinery supported by mechanization and intelligent technologies, as shown in Figure 2 [Figure 2: see original paper]. The smart orchard management system mainly includes subsystems for intelligent information acquisition, integrated water-fertilizer management, intelligent pest management, intelligent operation equipment, smart orchard management platform, and agricultural product traceability. The demonstration orchard integrated multiple information technologies, fundamentally solving problems of extensive management and low mechanization in traditional orchards, and essentially achieving unmanned management throughout the entire production process.

Although smart orchard construction is developing rapidly in China, most projects still lack complete information management platforms and intelligent operation machinery. Economic and technological development, combined with current labor shortages, clearly indicate that unmanned agricultural equipment represents the inevitable development direction of smart agriculture. This paper introduces the overall architecture and technical implementation details of a smart orchard constructed based on the author' s team' s understanding of current smart orchard development, serving as a pioneering demonstration for smart orchard promotion.

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2 Key Technologies for Smart Orchards

2.1 Intelligent Information Acquisition System

The information acquisition system forms the foundation for smart orchard management decisions, integrating multi-sensor data to provide basis for field management. Traditional methods rely on single data sources for calculation and decision-making, resulting in poor accuracy and anti-interference capability. In contrast, the intelligent information acquisition system for smart orchards includes air-ground collaborative multi-source perception devices, fixed pole station systems, and IoT sensors deployed in the field. Through multi-sensor information fusion, various vegetation indices, pest and disease information, temperature and humidity, wind speed and direction, soil and crop moisture information can be obtained for comprehensive decision-making. The system can also develop more accurate models based on historical data and manual intervention results to provide decision-making support.

The intelligent information acquisition system in the demonstration orchard mainly includes multi-spectral drones, ground pole station systems, ground information acquisition systems, and IoT sensors.

(1) Multi-spectral Drone

The DJI P4M multi-spectral drone (Figure 3 [Figure 3: see original paper]) is used for spectral information acquisition. Aerial images from different bands are combined and stitched to generate various vegetation index results (Figure 4 [Figure 4: see original paper]), which after further processing can reflect vegetation growth status, water stress conditions, and nutritional status. The RGB images obtained can also be used for remote diagnosis of pests and diseases.

(2) Ground Pole Station System

The ground pole station system includes fixed cameras in the field, IoT sensors, and mobile agricultural information acquisition systems. By installing monitoring cameras with optical zoom in the field (Figure 5 [Figure 5: see original paper]), crop growth status can be observed, replacing manual field patrols. The optical zoom function enables clear observation of pests and diseases on crops, with captured images uploaded to the system backend for automatic identification and early warning of pests and diseases using machine learning methods. Multi-element meteorological sensors (Figure 6 [Figure 6: see original paper]) can continuously obtain meteorological information including wind speed, wind direction, temperature, humidity, air pressure, and precipitation, uploading it in real time to the backend storage server. Fusion with other sensor information can provide decision-making support for integrated water-fertilizer management and plant protection operations.

(3) Ground Information Acquisition System

The research team developed a multi-functional agricultural information acquisition unmanned system (Figure 7 [Figure 7: see original paper]) equipped with a 16-line LiDAR, Real-Time Kinematic (RTK) differential positioning system, First Person View (FPV) camera, and industrial computer. This system can collect tree point cloud information and visible light RGB images. The LiDAR enables tree row recognition for autonomous navigation. After obtaining point clouds, tree volume and canopy density information can be calculated to provide support for plant protection spraying, tree pruning, and other orchard operations. RGB images captured at close range in tree rows enable remote diagnosis of pests and diseases. The RTK differential positioning system can record trajectories and obtain marker point coordinates to support path planning for unmanned agricultural machinery.

(4) IoT Sensors

IoT stem water potential sensors (Figure 8 [Figure 8: see original paper]) can accurately measure changes in water potential in fruit tree stems to obtain the actual water requirements of plants. Combined with soil nitrogen, phosphorus, and potassium information obtained from IoT soil sensors (Figure 9 [Figure 9: see original paper]), the integrated water-fertilizer system can be automatically controlled with reduced manual intervention.

2.2 Integrated Water-Fertilizer Management System

Based on the water-fertilizer integration pipeline system (Figure 10 [Figure 10: see original paper]), water and fertilizer management in the smart orchard is fully automated without manual intervention, effectively reducing labor input and saving nitrogen and potassium fertilizer application. By connecting a mixer to the IoT network, fertilizer and water are mixed together and then delivered through a fixed pipeline system pre-installed in tree rows for drip irrigation or spraying, achieving integrated water-fertilizer application. By integrating IoT water potential sensors and soil moisture sensors, the big data platform monitors crop water deficiency trends. When soil moisture content is insufficient, the system controls the integrated water-fertilizer system to start drip irrigation. The system also incorporates historical data from meteorological sensors to predict future rainfall, staggering drip irrigation with rainfall to maximize water utilization. Irrigation is also scheduled to avoid high-temperature noon periods, further saving water. The comprehensive water savings can reach 70%, while water-soluble fertilizers are delivered directly to plant roots through drip tapes, avoiding the low fertilizer utilization caused by application between tree rows. This achieves nitrogen savings of 20%–30% and potassium savings of 20%–35% throughout the growing season.

2.3 Intelligent Pest Management System

The general policy for plant protection in China is "prevention first, integrated control."For smart orchards, the core focus is fruit tree growth status, integrating physical, chemical, and biological control methods to effectively control pest occurrence at lower cost and with less environmental pollution. Traditional orchards often rely on manual inspection for pest monitoring, which is time-consuming and labor-intensive for large-scale and mountainous orchards, and heavily dependent on personnel experience.

In the smart orchard, the research team installed IoT pest monitoring lamps, IoT insecticidal lamps (Figure 11 [Figure 11: see original paper]), pest information collection and analysis systems (Figure 12 [Figure 12: see original paper]), and automatic spore capture systems. These devices complete pest and spore information collection, photographing captured pests and pathogen spores for upload to the server for identification and counting. Managers can conveniently view pest and disease conditions remotely through backend web pages or mobile apps. Combined with meteorological sensors and multi-spectral imagery, the system can predict pest and disease occurrence for preventive pesticide application. IoT insecticidal lamps represent a typical physical control method that is environmentally friendly, capable of capturing Lepidoptera and Coleoptera pests without the environmental pollution caused by chemical pesticides. Combined with sticky boards containing sex attractants, green control can be achieved. Through physical control by IoT insecticidal lamps and precise preventive pesticide application guided by pest monitoring systems, excessive chemical pesticide application is reduced, decreasing the number of pesticide applications by 3–5 times and reducing chemical pesticide usage by 20%–30% throughout the growing season.

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3 Intelligent Operation Equipment System

3.1 Overview of Intelligent Operation Equipment System

The intelligent operation equipment system forms the foundation for executing orchard management in smart orchards, with unmanned operation being its typical characteristic. With the development of IoT and unmanned driving technologies, the promotion of 5G technology, and its characteristics of high bandwidth and low latency, remote control of unmanned operation machinery has become more feasible. Unmanned driving technology not only reduces labor input during production but also ensures high-quality operation through more accurate travel paths. Compared with traditional agricultural machinery, human-machine separation significantly improves operator safety, reducing the possibility of injury during mowing and shredding operations and minimizing heatstroke and poisoning risks during plant protection operations. The remote field patrol system can automatically monitor field pest and disease conditions, while plant protection operations utilize coordinated air-ground machinery. Compared with traditional spray guns, this approach saves more than 30% of pesticides per operation while requiring only one person to add chemicals at the field edge. Therefore, labor input can be reduced by more than 50% during field management stages.

The main intelligent operation equipment in the smart orchard constructed in this study includes unmanned lawn mowers, intelligent anti-freeze machines, trenching and fertilizing machines, autonomous tracked intelligent profiling variable sprayers, six-rotor branch-to-target drones, multi-functional picking platforms, and finishing and pruning machines, with main parameters shown in Table 1 .

Table 1 Parameters of intelligent operation equipment in smart orchard

Equipment	Parameters
Unmanned lawn mower	Travel speed: 3-5 km/h; Operation efficiency: 1500–2000 m^2/h
Intelligent anti-freeze machine	Heating power: >5500 W; Fan power: 750 W; Fan flow: 1380 m^3/h; Air outlet wind speed: 23 m/s; Effective air supply distance: 50 m
Trenching and fertilizing machine	Fertilizer tank volume: 0.5 m^3; Trenching width: 35 cm; Fertilizing depth: 20–40 cm; Fertilizer discharge rate: 0.5–5 kg/m; Matching power: 29–44 kW
Autonomous tracked intelligent profiling variable sprayer	Tank capacity: 200 L; Maximum travel speed: 5 km/h; Spray working pressure: 0–4 MPa; Nozzle quantity: 10; Pump flow: 13–22 L/min; Operation efficiency: 13.33 hm^2/h
Six-rotor branch-to-target drone	Tank capacity: 30 L; Maximum operation speed: 7 m/s; Spray working pressure: 0–0.5 MPa; Nozzle quantity: 8; Spray width: 4–7 m; Pump flow: 0–3.6 L/min; Operation efficiency: 0.67 hm^2/h; Endurance: 5–8 h
Multi-functional picking platform	Ground clearance: 76 mm; Motor power: 1500 W; Platform maximum height: 2150 mm; Travel speed: 3–5 km/h
Orchard finishing and pruning machine	Top cutting blade quantity: 4; Vertical cutting blade quantity: 5; Top maximum cutting height: 4 m; Vertical maximum cutting height: 5.4 m; Self-weight: 400 kg; Maximum cutting diameter: 8 cm

3.2 Main Intelligent Operation Equipment Systems

(1) Unmanned Lawn Mower

Inter-row grass cover in orchards regulates ground temperature and improves soil ecological environment. Inter-row grass management requires regular trimming to reduce pest breeding and facilitate field operations. Unmanned lawn mowers can independently complete weeding operations. The unmanned self-propelled lawn mower independently developed by the Unmanned System Research Institute of China Agricultural University (Figure 13 [Figure 13: see original paper]) can mow at a rate of 1500–2000 m^2/h and features a shredding function that directly breaks down grass after mowing, facilitating subsequent mechanized operations. The mower uses hybrid power, with the engine simultaneously providing power for both mowing and travel during operation, ensuring operation effectiveness and endurance. Compared with pure electric models, it offers better operational continuity, while the fuel-powered mowing mechanism ensures better operation results.

(2) Intelligent Anti-Freeze Machine

Orchard frost damage can greatly affect yield. "Late spring coldness" occurring during the flowering period, if lasting too long, can cause flower cluster frostbite or even death, potentially resulting in total crop loss. The intelligent thermal fogger connected within the smart orchard can achieve frost prevention. When the meteorological sensor system detects temperatures below crop tolerance thresholds, the IoT system remotely activates the intelligent thermal fogger. Through electric heating and air supply systems, air circulation near the ground surface is promoted (Figure 14 [Figure 14: see original paper]), slowing down temperature drops.

(3) Trenching and Fertilizing Machine

Traditional orchard water-fertilizer management requires manual flood irrigation and trenching fertilizing machines for base and top dressing, involving high labor intensity and manpower requirements. Flood irrigation generally requires two to three people working simultaneously, while trenching fertilizing machines require one person to drive the machine and another to assist with fertilizer addition. The trenching and fertilizing machine connects to the IoT through an onboard terminal, uploading real-time machine location, Power Take Off (PTO) shaft speed, and other operation status data. The IoT backend can monitor and evaluate operation quality and area. Trenching and fertilizing can be completed in one pass, with low center of gravity and flexible operation, adapting to different terrains and soil conditions (Figure 15 [Figure 15: see original paper]).

(4) Autonomous Tracked Intelligent Profiling Variable Sprayer

The autonomous tracked intelligent sprayer is equipped with LiDAR and RTK differential positioning systems, achieving autonomous path planning, tree row recognition navigation, and obstacle avoidance. The spray system is gasoline engine-driven, ensuring overall sprayer endurance. Each nozzle is equipped with a solenoid valve, enabling target spraying based on tree point clouds detected by LiDAR, reducing pesticide usage. The autonomous sprayer uses 5G technology to connect to the smart orchard backend management system, uploading operation information in real time. The backend can record operation area and evaluate operation effectiveness. After fusing data from the pest monitoring system and multi-functional agricultural information acquisition unmanned system, the backend management system can generate operation prescription maps for coordinating profiling variable spray machinery (Figure 16 [Figure 16: see original paper]).

(5) Six-Rotor Branch-to-Target Drone

The six-rotor branch-to-target drone (Figure 17 [Figure 17: see original paper]) can perform aerial plant protection operations on fruit trees. Using a branch-to-target flight mode that changes the aircraft structure, the wind field penetrates along branch directions into the tree canopy, effectively improving the penetration deficiency of plant protection drone spraying. Through the supporting management platform, one controller can operate multiple drones, further improving operation efficiency. Front and rear dual FPV videos can be connected to the backend management platform for remote flight status monitoring, ensuring operation safety and quality.

(6) Multi-Functional Picking Platform

The multi-functional electric tracked lifting operation platform is compact in size, with strong passability through tracked chassis. It features multi-purpose functionality and can enter various complex terrains for operations. The lifting platform and extendable left-right working positions can adapt to orchards with different row spacing and planting patterns. The platform can be used during flower and fruit thinning, tree management, and picking and transportation operations (Figure 18 [Figure 18: see original paper]).

(7) Finishing and Pruning Machine

The tree finishing and pruning machine can be used for autumn pruning, mounted in front of a tractor for tree pruning, saving labor and materials with high operation efficiency. The maximum pruning diameter can reach 8 cm. Mounting on the front side of the machine provides good visibility, ensuring pruning effectiveness (Figure 19 [Figure 19: see original paper]).

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4 Smart Orchard Management Platform

All IoT sensors, intelligent agricultural machinery, integrated water-fertilizer systems, fruit traceability, and video monitoring equipment in the smart orchard are connected to the backend storage server through 5G and other communication technologies. The management platform (Figure 20 [Figure 20: see original paper]) obtains data from the database through Application Programming Interface (API) for visualization. On the management platform, users can view and control cameras, check sensor historical data, and develop switching strategies for automated systems such as insecticidal lamps and integrated water-fertilizer systems. By utilizing historical data and multi-sensor information fusion for decision-making, the system can integrate more data sources than manual operation to achieve better control effects.

The information acquisition platform can obtain tree growth information, and the big data visualization platform (Figure 21 [Figure 21: see original paper]) aggregates and displays data from sensors and monitoring cameras. The agricultural machinery management platform automatically schedules operation machinery by accessing sensor data from the big data platform. For example, when the pest monitoring system detects high probability of pest occurrence, the system automatically schedules operation machinery for preventive pesticide application, controlling pests before outbreaks and effectively reducing labor input. Using the agricultural product traceability platform, production and sales information can be traced through QR codes on fruit packaging. After scanning the code, consumers can view fruit production and sales records stored in the management backend.

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5 Conclusions and Outlook

The smart orchard presented in this study addresses labor shortages and low production efficiency by integrating IoT, big data, and intelligent agricultural machinery technologies, achieving digitalized agricultural operation decision-making, full-process mechanization, and green ecology. This forms a replicable and promotable pioneering demonstration experience for smart orchards. Comparative analysis revealed that implementing the smart orchard management model reduced labor costs by over 50%, pesticide usage by 30%-40%, fertilizer usage by 25%-35%, and irrigation water consumption by 60%-70%, while achieving a 32.5% increase in economic benefits. Smart orchard construction significantly improves agricultural production technology levels, alleviates labor shortages caused by aging to some extent, improves the surrounding ecological environment, and closely integrates targeted poverty alleviation with ecological protection, holding significant practical meaning for building beautiful villages and a beautiful China.

Despite certain achievements in smart orchard construction, there remains a gap from the modern goals of full mechanization, complete intelligence, and unmanned production, with many unresolved issues throughout the industry that warrant deep consideration from government management departments, research institutes, equipment manufacturers, application and promotion departments, and farm owners.

(1) Poor mechanization conditions in most orchards, especially traditional old orchards. Land parcels are fragmented and not contiguous, with non-contour planting and lack of continuous passages for intelligent machinery operation. The distance between machinery storage and field plots is long, resulting in low operation efficiency and excessive energy loss during transfer, particularly for electric-driven intelligent equipment.

(2) Insufficient innovation capacity for specialized orchard mechanization machinery and newly developed intelligent equipment and systems. Practical application during the development of fully autonomous operation intelligent equipment and backend management system integration revealed that current technology development often adopts autonomous driving and high-speed operation frameworks from existing automotive and other industries. There is a lack of specialized intelligent equipment for Chinese orchards characterized by low-speed travel, heavy loads, low ground clearance, and strong climbing ability, as well as unified development frameworks suitable for large-area plot operation planning. Current equipment mostly has independent functions without forming an integrated system, making intercommunication difficult. Future specialized autonomous orchard intelligent equipment requires a more flexible, complete, and systematic software architecture to handle driving, operation, and other functions.

(3) Lack of professional sensors in smart orchard systems (some professional sensors are entirely imported), and different manufacturers lack unified communication formats. Accessing sensors requires developing drivers for each type, creating substantial workload and additional failure points. Some special sensors are currently completely dependent on imports with high prices. Sensors used in smart orchards (smart agriculture) involve multiple disciplines, and government functional departments should increase efforts to encourage enterprises and universities to invest in sensor research and development to achieve domestic substitution of key agricultural sensors.

(4) Insufficient integration among subsystems in smart orchards, with relatively loose crop management models and few parameters for cross-model fusion use, lacking almost any universality. To improve the precision of orchard mechanized operations, more comprehensive and universally applicable crop growth models containing more parameters are needed to guide operation planning. More complete benefit analysis of smart orchards is also required, along with tighter integration of various systems to facilitate true mechanization and intelligence of smart orchard production systems for better socio-economic benefits.

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