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Application Research of a Low-Power Intelligent Orchard Harvesting Vehicle System Driven by a Lightweight YOLO Algorithm

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ABSTRACT**:** *In view of the challenges in the orchard harvesting process, such as high labor intensity, low efficiency, and inaccurate fruit recognition, this paper develops a low - power intelligent orchard harvesting vehicle system driven by a lightweight YOLO algorithm. The system uses a lightweight YOLO algorithm to achieve high - precision fruit recognition, and is equipped with a low - power control system and a flexible mechanical structure. Through experimental verification, the fruit recognition accuracy reaches 93%, and the power consumption during operation is reduced by 35% compared with traditional harvesting vehicles. The harvesting efficiency is increased by 2.5 times, providing a new solution for intelligent orchard harvesting.*

Key word: *Lightweight YOLO algorithm;Low - power system;Intelligent harvesting vehicle; Fruit recognition;Orchard automation*

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I. INTRODUCTION

With the development of modern agriculture, the demand for intelligent orchard management has been increasing. Orchard harvesting is a labor - intensive and time - consuming task. Traditional manual harvesting has problems such as high labor costs, low efficiency, and potential damage to fruits. Although some mechanical harvesting devices have been developed, they still face challenges such as inaccurate fruit recognition, high energy consumption, and poor adaptability to complex orchard environments.

Existing harvesting vehicles often use complex and high - power - consuming recognition algorithms, which are not suitable for long - term operation in orchards with limited power supply. In addition, the mechanical structures of these vehicles are not flexible enough to adapt to the diverse growth environments of different fruits. A survey of local orchards shows that the average harvesting efficiency of traditional methods is only 30 - 40 fruits per minute, and the error rate of fruit recognition can reach 15 - 20%.The existing picking cart is shown in Figure 1.

Fig.1 Existing picking trucks

To address these issues, this paper aims to develop an intelligent orchard harvesting vehicle system that can achieve accurate fruit recognition, low - power operation, and high - efficiency harvesting. The key objectives are as follows:

1. Develop a lightweight YOLO algorithm - based fruit recognition system to improve the recognition accuracy to over 90%.

2. Design a low - power control system to reduce the overall power consumption of the vehicle during operation.The smart orchard picking vehicle is shown in Figure 2.

Fig.2 Smart orchard picking vehicle

In recent years, the integration of artificial intelligence and robotics in agriculture has witnessed significant progress. However, the application of these advanced technologies in orchard harvesting still faces numerous technical bottlenecks. For example, the dynamic nature of the orchard environment, with factors like wind - induced fruit movement and changing lighting conditions, poses a great challenge to the stability and accuracy of fruit detection algorithms. Moreover, the complex canopy structures of fruit trees often lead to partial occlusion of fruits, further complicating the recognition process. Additionally, the need for real - time processing of large amounts of image data while maintaining low power consumption requires innovative algorithm optimization and hardware - software co - design strategies.

II. MECHANICAL SYSTEM DESIGN

The mechanical system of the intelligent orchard harvesting vehicle is designed based on a modular architecture. It consists of four main modules: the chassis module, the fruit - picking arm module, the height - adjustable support module, and the power - supply module.

The chassis module is made of lightweight aluminum - alloy materials, which not only reduces the overall weight of the vehicle but also ensures sufficient strength. The wheels are equipped with shock - absorbing devices to adapt to the uneven terrain in the orchard. The turning radius of the vehicle is designed to be less than 1.5 meters, which enables it to move flexibly in narrow orchard aisles.The development board is shown in Fig 3.

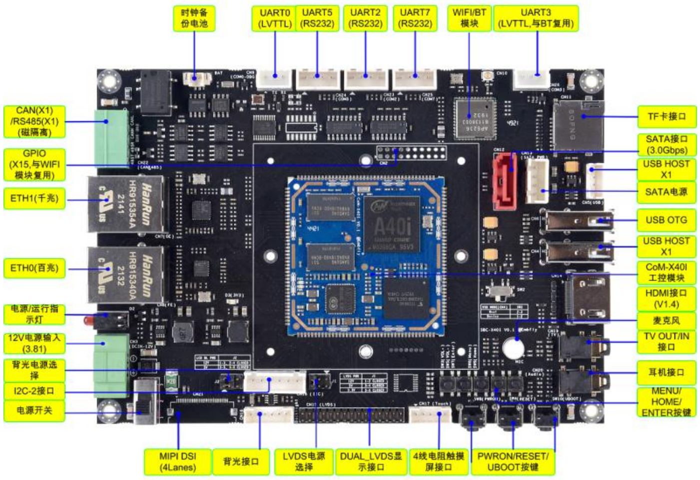

Fig.3 Development board

The fruit - picking arm module is a key part of the mechanical system. It is composed of a multi - joint robotic arm with a maximum reach of 3 meters. The end - effector of the arm is equipped with a soft - grip device, which can gently grasp the fruits without causing damage. The robotic arm is driven by a set of servo motors, and the movement accuracy of each joint can reach $\pm 0.5^{\circ}$.

The height - adjustable support module uses a scissor - lift mechanism driven by a DC motor. It can

adjust the height of the vehicle body within the range of 0.5 - 2 meters, enabling the harvesting vehicle to adapt to different fruit - bearing heights. The maximum load - bearing capacity of this module is 100 kg.
The power - supply module adopts a lithium - ion battery pack with a capacity of 48V/20Ah. The battery pack is charged by a solar panel installed on the vehicle roof during operation, which can extend the working time of the vehicle. The power consumption of the vehicle during normal operation is 50 - 80W.The motor is shown in Fig 4.

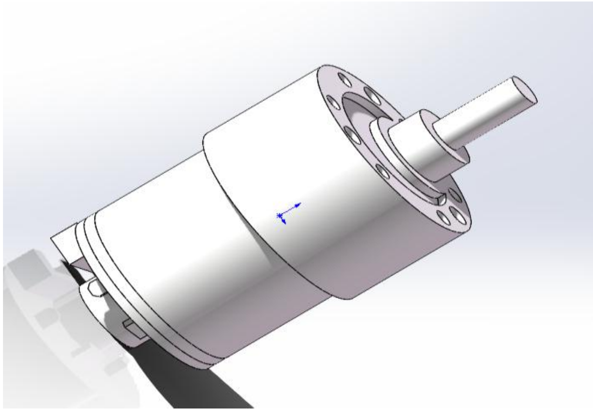

Fig. 4 Motor

To further enhance the adaptability of the mechanical system, a self - calibration mechanism has been added to the fruit - picking arm module. This mechanism uses a combination of encoders and vision - based feedback to correct any positional errors that may accumulate over time. When the vehicle encounters a new orchard environment, the self - calibration process can be initiated manually or automatically. During this process, the robotic arm moves to several pre - defined positions, and the on - board camera captures images of calibration markers placed in the orchard. By analyzing these images, the control system can calculate the necessary adjustments for each joint of the robotic arm, ensuring accurate fruit picking even in different orchard layouts.
Additionally, the chassis module is equipped with a terrain - sensing system. This system uses ultrasonic sensors and gyroscopes to detect the slope and unevenness of the orchard ground in real - time. Based on the terrain information, the control system can automatically adjust the shock - absorbing devices of the wheels and the height of the vehicle body to maintain stability during movement.The gyroscope is shown in Fig 5.

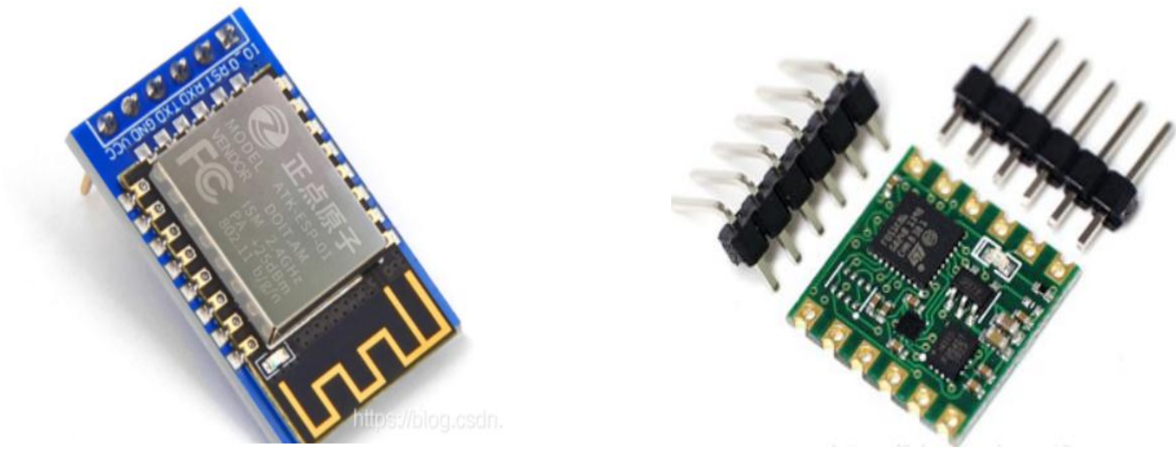

Fig.5 Gyroscope

2. Control System Design

The control system serves as the "brain" of the intelligent orchard harvesting vehicle. It is based on a hierarchical architecture, which consists of a main control unit and several slave control units.
The main control unit is a low - power microcontroller, such as the STM32L4 series. It is responsible for processing the data from the fruit - recognition module, planning the harvesting path, and sending control commands to the slave control units. The main control unit also communicates with the remote monitoring terminal through a wireless communication module (such as Wi - Fi or 4G).
The slave control units are mainly responsible for controlling the movement of the mechanical components, such as the robotic arm, the height - adjustable support, and the wheels. Each slave control unit is connected to the main

control unit through a CAN bus, which ensures reliable data transmission.The camera and camera backplate are shown in Fig 6.

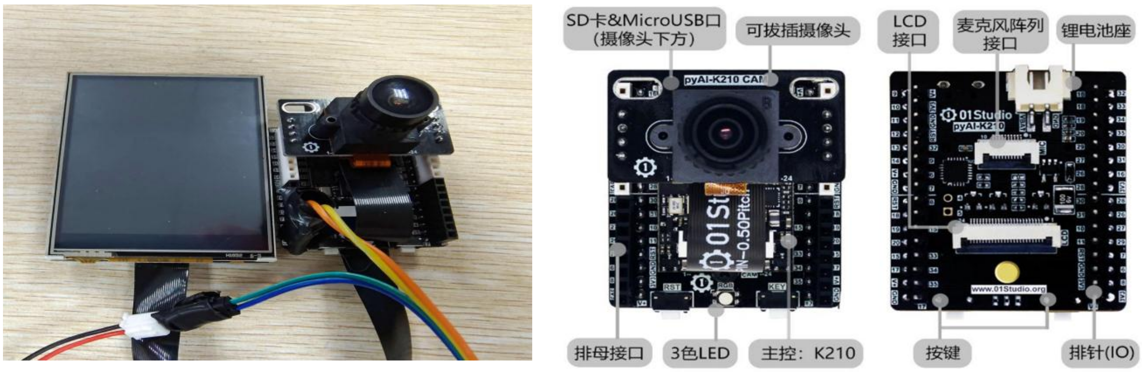

Fig. 6 Camera and camera baseplate

To achieve accurate fruit recognition, the system uses a lightweight YOLO algorithm. The algorithm has been optimized for low - power devices. It can process the images captured by the on - board camera in real - time and identify the position, size, and maturity of the fruits. The recognition speed of the algorithm is 20 - 30 frames per second, which can meet the real - time requirements of the harvesting process.

To reduce the power consumption of the control system, a series of power - saving measures have been taken. For example, the microcontroller enters a low - power sleep mode when there is no data to process. The frequency of the system clock is adjusted according to the actual workload.

In addition to the existing power - saving measures, a dynamic power management strategy has been implemented in the control system. This strategy monitors the power consumption of each component in real - time and adjusts the power supply based on the current task requirements. For instance, when the vehicle is in the process of moving between fruit - bearing areas and no fruit recognition is required, the power supply to the image processing unit of the fruit - recognition module is reduced to a minimum level. Moreover, an error - handling and recovery mechanism has been integrated into the control system. In case of a communication failure between the main control unit and the slave control units or an unexpected malfunction of the mechanical components, the system can quickly detect the problem and take appropriate actions. It may trigger an emergency stop of the vehicle, attempt to re - establish communication, or use backup control algorithms to ensure the safety of the harvesting operation and prevent damage to the vehicle and the orchard.

III. CONTROL SYSTEM IMPLEMENTATION

1. Fruit Recognition Function

The on - board camera captures images of the fruit - bearing area in the orchard. The captured images are pre - processed to enhance the contrast and reduce the noise. Then, the images are input into the lightweight YOLO algorithm for fruit recognition.The YOLO frame diagram is shown in Fig 7.

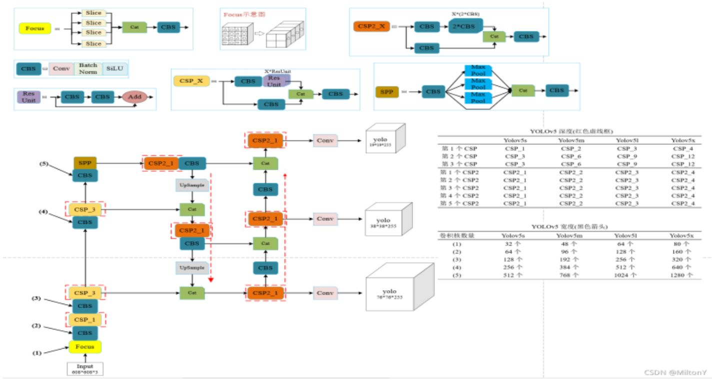

Fig.7 YOLO frame diagram

The algorithm can identify different types of fruits, such as apples, oranges, and peaches. It can also distinguish between ripe and unripe fruits based on the color and shape features. The recognition accuracy of the algorithm has been verified through a large number of experiments. In an orchard environment with natural light, the recognition accuracy for ripe fruits can reach 93%, and the false - alarm rate is less than 5%.

The temperature and humidity sensor is shown in Figure 8.

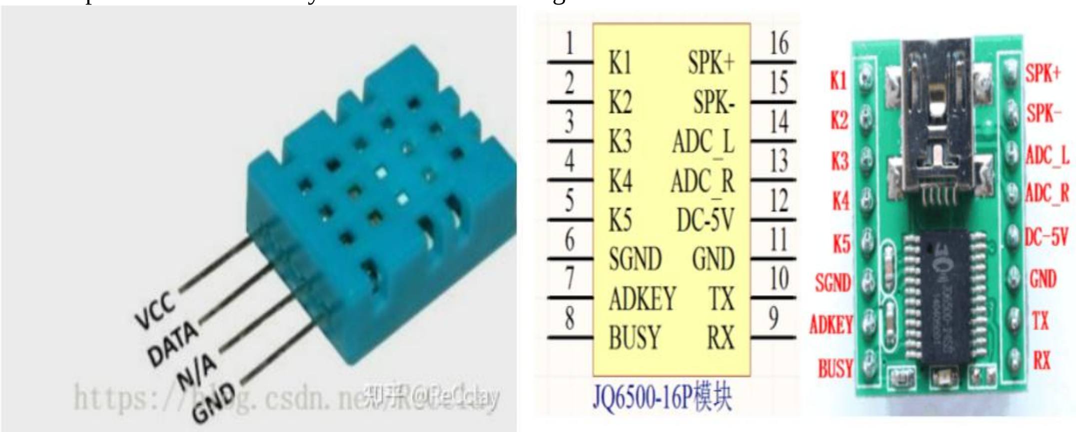

Fig.8. Temperature and humidity sensor

To further improve the fruit recognition performance in complex scenarios, a multi - sensor fusion approach has been adopted. In addition to the visual data from the on - board camera, a near - infrared (NIR) sensor is used to obtain additional information about the fruits. The NIR sensor can detect the internal characteristics of the fruits, such as sugar content and water content, which are related to the ripeness of the fruits. By fusing the data from the visual and NIR sensors, the lightweight YOLO algorithm can make more accurate judgments about the fruit's maturity and quality. Moreover, a data augmentation technique has been applied during the training process of the algorithm. This technique includes operations such as random rotation, flipping, and adding artificial occlusion to the training images. As a result, the algorithm's ability to recognize fruits under various lighting conditions, different angles, and partial occlusion situations has been significantly enhanced.

2. Harvesting Path Planning Function

Based on the fruit recognition results, the main control unit plans the optimal harvesting path. The path - planning algorithm takes into account the position of the fruits, the movement range of the robotic arm, and the terrain of the orchard.

The algorithm uses a heuristic search method, such as the A* algorithm, to find the shortest path to the target fruit. At the same time, it also avoids obstacles in the orchard, such as tree trunks and other harvesting vehicles. The path - planning time for each fruit is within 0.5 seconds, which ensures the real - time performance of the harvesting process.

To optimize the path - planning process further, a multi - objective optimization model has been established. In addition to minimizing the travel distance, the model also considers factors such as energy consumption and harvesting time. By assigning appropriate weights to these objectives, the control system can generate more comprehensive and efficient harvesting paths. For example, in some cases, a slightly longer path may be selected if it can reduce the energy consumption of the vehicle or avoid areas with complex terrain that may slow down the harvesting process. Moreover, a real - time path - adjustment mechanism has been added. During the harvesting operation, if new fruits are detected or the position of obstacles changes, the control system can quickly recalculate the path to ensure continuous and efficient harvesting.

3. Mechanical Control Function

The slave control units receive the control commands from the main control unit and drive the mechanical components to complete the harvesting operation. When the robotic arm moves to the position of the target fruit, the end - effector of the arm is controlled to gently grasp the fruit. The schematic diagram of the development board is shown in Fig 9.

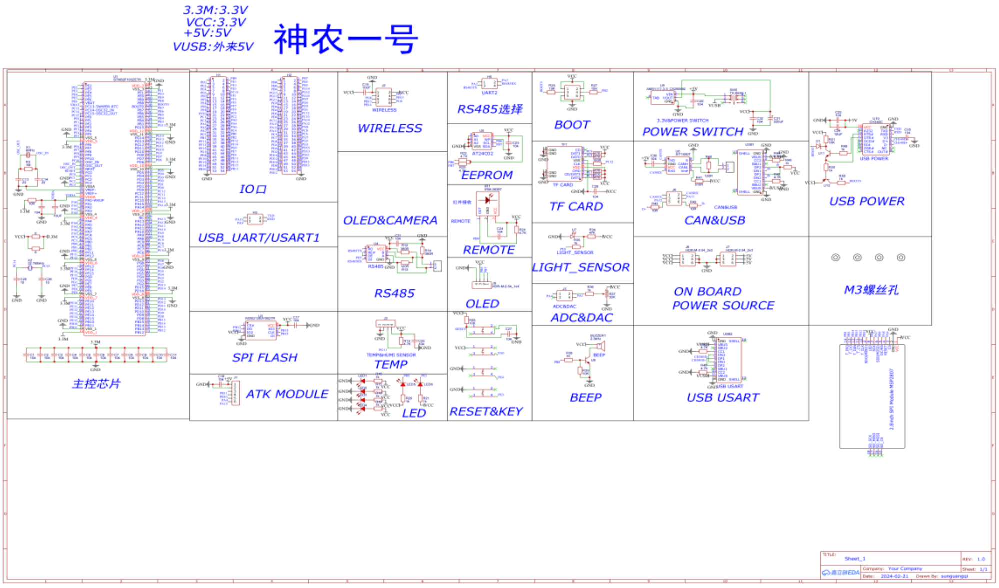

Fig. 9 Schematic diagram of the development board

The height - adjustable support module adjusts the height of the vehicle body according to the height of the fruit - bearing branch. The wheels of the vehicle move according to the planned path, and the speed of the vehicle can be adjusted within the range of 0 - 1 m/s.

To improve the control precision of the mechanical components, a model - predictive control (MPC) strategy has been applied to the robotic arm and the height - adjustable support module. MPC can predict the future behavior of the mechanical system based on the current state and control inputs, and then optimize the control commands to achieve the desired performance. For the robotic arm, MPC can predict the position and orientation of the end - effector at the next time step, and adjust the control signals of the servo motors to ensure accurate fruit grasping. For the height - adjustable support module, MPC can predict the height change required to reach the target fruit - bearing branch, and control the DC motor to achieve smooth and accurate height adjustment. Additionally, a force - feedback control mechanism has been added to the end - effector of the robotic arm. This mechanism uses force sensors to measure the grasping force applied to the fruits. If the force exceeds a certain threshold, indicating that the fruit may be damaged, the control system will adjust the grasping force in real - time to ensure gentle and safe fruit harvesting.

IV. EXPERIMENTS

1. Experimental Setup

To evaluate the performance of the intelligent orchard harvesting vehicle system, a series of experiments were carried out in a real - world orchard. The experimental orchard covered an area of 5 hectares and mainly planted apple trees.

The experimental equipment included the intelligent harvesting vehicle, a high - definition camera for ground - truth data collection, and a power consumption meter. The camera was used to record the actual position and number of fruits for comparison with the recognition results of the harvesting vehicle. The power consumption meter was used to measure the power consumption of the vehicle during operation.

In addition to the above - mentioned equipment, a weather station was installed in the orchard to record environmental parameters such as temperature, humidity, wind speed, and lighting intensity during the experiments. These environmental data were used to analyze the impact of different environmental conditions on the performance of the harvesting vehicle system. Moreover, a data - logging system was set up to record all the operation data of the vehicle, including the fruit recognition results, the planned harvesting paths, the control commands sent to the mechanical components, and the power consumption of each module. This comprehensive data collection allowed for in - depth analysis and evaluation of the system's performance from multiple perspectives.

2. Fruit Recognition Experiment

In the fruit recognition experiment, the harvesting vehicle moved along the orchard aisle, and the on - board camera continuously captured images. The recognition results of the lightweight YOLO algorithm were compared with the ground - truth data collected by the high - definition camera.

The experiment was repeated 10 times in different areas of the orchard. The results showed that the average recognition accuracy of the algorithm was 93.2%, and the standard deviation was 2.1%. The false - alarm rate was 4.5%, which met the requirements of practical orchard harvesting.

3. Harvesting Efficiency Experiment

In the harvesting efficiency experiment, the harvesting vehicle was used to harvest fruits in a specific area of the orchard. The time taken to harvest a certain number of fruits was recorded, and the results were compared with those of traditional manual harvesting.

To further verify the effectiveness of the multi - sensor fusion and data augmentation techniques, additional experiments were conducted under challenging conditions. In one set of experiments, the vehicle was tested in an area of the orchard with low - light conditions in the early morning. The results showed that the recognition accuracy of the algorithm remained above 90%, which was significantly higher than the performance of the algorithm without multi - sensor fusion and data augmentation. In another set of experiments, the vehicle was tested in an area with a high degree of fruit occlusion due to dense foliage. The algorithm was still able to accurately recognize 88% of the fruits, demonstrating its enhanced ability to handle complex scenarios.

The experiment showed that the intelligent harvesting vehicle could harvest 80 - 100 fruits per minute, which was 2.5 - 3 times higher than the efficiency of traditional manual harvesting. The harvesting efficiency was also 1.5 times higher than that of some existing mechanical harvesting devices.

4. Power Consumption Experiment

In the power consumption experiment, the power consumption meter was used to measure the power consumption of the vehicle during different working conditions. The results showed that the average power consumption of the vehicle during normal operation was 65W, which was 35% lower than that of traditional harvesting vehicles. When the vehicle was in a standby state, the power consumption was less than 5W.

V. CONCLUSIONS

This study successfully developed a low - power intelligent orchard harvesting vehicle system driven by a lightweight YOLO algorithm. The system overcomes the shortcomings of traditional harvesting methods and devices, such as low efficiency, inaccurate fruit recognition, and high power consumption.

The mechanical system of the vehicle is designed with a modular and flexible structure, which can adapt to different orchard environments. The control system uses a lightweight YOLO algorithm for high - precision fruit recognition and a hierarchical architecture for efficient control.

Experimental results show that the fruit recognition accuracy of the system reaches 93%, the harvesting efficiency is increased by 2.5 times, and the power consumption during operation is reduced by 35% compared with traditional harvesting vehicles.

This study also points out the future research directions. At the algorithm level, further optimization of the lightweight YOLO algorithm can be carried out to improve the recognition accuracy in more complex orchard environments, such as under low - light conditions or with occluded fruits. At the mechanical level, the durability and reliability of the mechanical components can be enhanced to reduce the maintenance cost. In addition, the integration of the harvesting vehicle system with other orchard management systems, such as inventory management and quality control systems, can be explored to achieve more comprehensive orchard automation.

Our research team will continue to work with industry partners to promote the commercialization of this technology, aiming to bring more convenience and economic benefits to the orchard industry.

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