Asia Pacific
Academy of Science Pte. Ltd.

REVIEW ARTICLE

Research status of agricultural robot technology

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ABSTRACT

According to the different agricultural production uses, agricultural robots were classified, mainly including agricultural information collection robots, pruning robots, grafting robots, transplanting robots, spraying robots and picking robots. The research status of mainstream agricultural robots at home and abroad were introduced, and their working principles and characteristics were expounded. Finally, the problems existing in the key technologies of existing agricultural robots and their future development directions were put forward.

Keywords: agricultural robot; research status; key technology; intelligent

1. Introduction

At present, the world is highly concerned about agricultural robot technology. The research on agricultural robots in the United States, Japan, Spain, and South Korea started earlier, and the development is more perfect, but the agricultural robots developed by them are usually complex and bulky, which is not consistent with our agricultural art, so it is of great significance to develop agricultural robots in line with our agricultural situation. The relevant research began in the 1990s. Scientific research personnel have studied a variety of agricultural machinery, but it has not been realized to be industrialized. In recent years, the development of automation technology, computer control, image recognition, and sensor and signal processing industries in our country has promoted the renewal and development of agricultural robots[1–3].

As a major agricultural country in our country, many farmland operations, such as pruning, grafting, transplantation, spraying, picking, etc., still require manual operations that are time-consuming, low-efficiency, and high-cost. With the rise of big data and artificial intelligence technologies, as well as the emergence of new types of agriculture such as facility agriculture and precision agriculture, new technologies are constantly being applied to the agricultural robotics industry. The development of intelligent agricultural robots that can achieve high efficiency, low-loss operation, and solve the problems existing in traditional agriculture has become one of the most important development trends in agricultural machinery in the 21st century.

2. Research status of agricultural robot models

The diversity of agricultural production types leads to the diversification of agricultural robots, which

mainly include grafting robots, transplanting robots, spraying robots, agricultural information collection robots, pruning robots, and picking robots. This paper analyzes the research status of mainstream agricultural robots on the market and discusses their key technologies.

2.1. Foreign research status

2.1.1. Agricultural information collection robot

In order to improve the efficiency of agricultural information collection and reduce crop damage, Kyoto University developed a small hexapod robot to collect soil nutrients, temperature and humidity, plant growth, and other information[4]. The machine is composed of several servo motors, microcomputers, infrared ranging sensors (IRDMSs), etc. It adopts leg movement to improve maneuvering performance on obstacles and irregular ground, as shown in **Figure 1**. When working, obstacles are detected and avoided by two IRDMS sensors mounted on the face of the hexapod robot. The walking speed of the robot is adjustable, ranging from 16.7 m/s to 33.4 m/s.
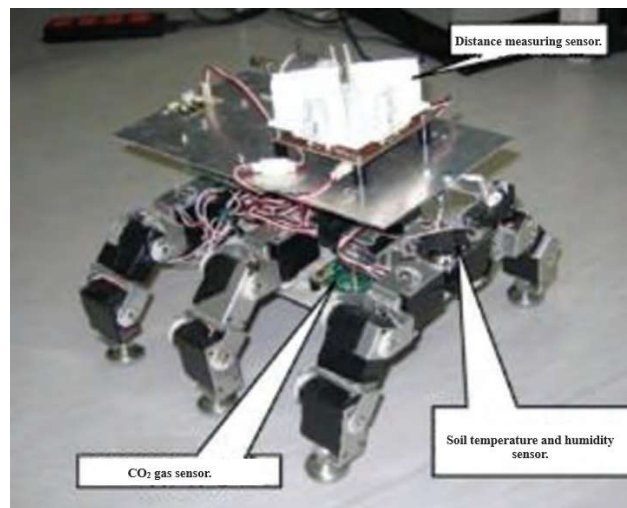
Figure 1. Small hexapod robot.

In order to effectively and timely collect production-related information to support precise agricultural decisions, the "observation dog robot" developed by Lida et al.[5] consists of a frame, a variety of sensors, a ranging system, a camera and GPS receiver, etc., as shown in **Figure 2**. The SICK laser measurement system is used to guide the canine robot, which uses four independently suspended driving wheels and a flexible steering mechanism to ensure smooth movement, a magnetic compass to sense its turning angle, a camera to look for diseased crops or weeds, and GPS to locate and record the data. The machine can automatically turn at the end of the row and enter the next row with a speed of 0.14 m/s.
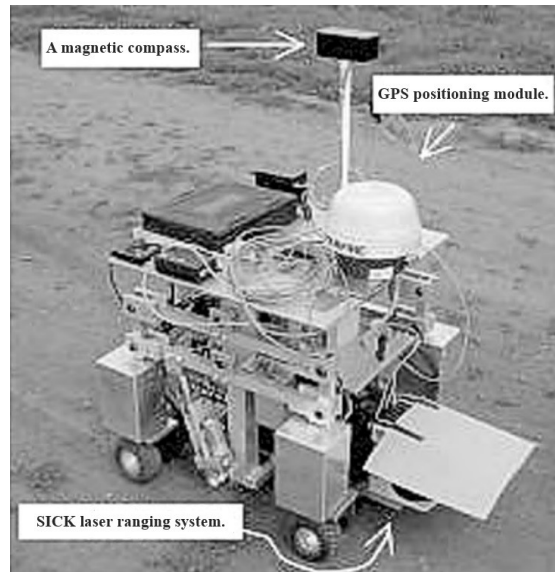
Figure 2. "Observing dog" information gathering robot.

The API autonomous agricultural robot developed by Aalborg University in Denmark is composed of a wheel module, a camera, a propulsion platform, and a control system and is suitable for farmland information collection of crops with a row spacing of 0.25–0.50 m, as shown in **Figure 3**[6]. The control system is composed of an embedded controller and an electronic control system for the vehicle, equipped with a camera for navigation and weed detection. The propulsion platform and the four-wheel drive and steering system are modular to improve their mobility. The vehicle can travel along predetermined paths, collect detailed field information, map weed populations in the field, and determine pesticide, fertilizer, and water application rates to facilitate the management of plants and plots in the field.
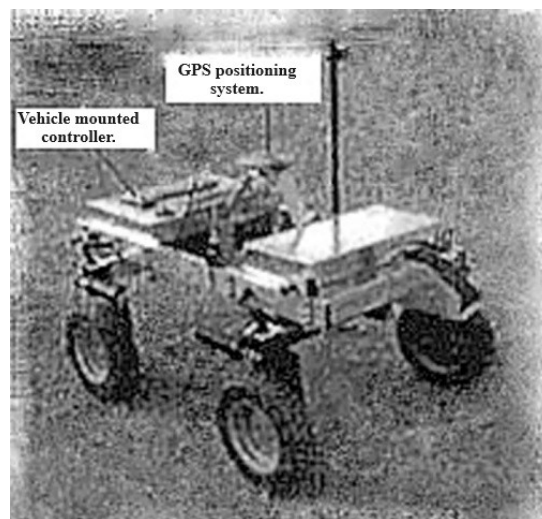
Figure 3. Autonomous agricultural robot.

Deere Company TD Pickett developed robots for soil testing, including a ground drive system, sampling probe, microlaboratory, etc.[7]. The steering and positioning of the robot are controlled by a control unit. The robot carries a kit containing one or more probes for extracting soil samples. After extracting the soil sample, the unearthed sample data can be detected and analyzed by the micro-laboratory on the robot, and the data can be stored or transmitted remotely.

2.1.2. Pruning robot

In 2010, an American company developed the second generation of grape pruning robots and demonstrated them in a vineyard in Lodi, California. The operation of the robot was guided by machine vision, and the pruning of grape branches was completed by two robotic arms, as shown in **Figure 4**[8]. In order to improve the accuracy of operation and avoid the influence of natural light, the working part of the machine adopts a closed installation and has a light source to avoid the influence of an external light source. The pruning cost is $0.17 per grape, which is lower than the manual pruning cost of $0.35 per grape, which can effectively improve the efficiency of vineyard production management and reduce the labor cost.

Figure 4. Second generation grape trimming robot prototype from Lodi, California, USA.

In 2010, a grape branch pruning robot developed in Christchurch City, New Zealand, was jointly developed by engineers from the University of Canterbury and the University of Lincoln in the UK, as shown in **Figure 5**[9]. Using 3D camera technology, the robot can measure the distance between the machine and the target vine while the equipment is moving. It also has night vision functions and can operate all day. It plays an important role in improving the quality of berries and labor efficiency.

Figure 5. New Zealand grape trimming robot.

2.1.3. Grafting robot

In 1986, Japan took the lead in the study of grafting machines and carried out three generations of prototype exploration. For melons and solanum crops, in 1994, Japan Iseki Company and Japan Institute of Science and Research jointly developed the GR800B type semi-automatic grafting machine and the GR800T type semi-automatic grafting machine, as shown in **Figure 6**. The machine adopts the grafting method, using a fixed grafting clip; operation needs two people to cooperate with the stock and scion; grafting efficiency is 800 plants/h; grafting success rate is 90%; and in 2010, it was improved. In 1994, the Japanese Yanma Company developed the AG1000 type of automatic fruit grafting machine, as shown in **Figure 7**. It only needs

one person to operate and can graft eight plants at a time. The grafting efficiency is up to 1000 plants/h, and the success rate is up to 97%. However, its complex structure and high requirements for rootstock and scion did not achieve mass production. In 2011, the GRF800-U type automatic grafting machine, which was jointly developed by the Japanese Igseki Company and the Japanese Institute of Health and Research, adopted the grafting method, and the grafting efficiency is up to 800 plants/h, but the price is expensive.

Figure 6. Japan GR800T semi-automatic grafting machine.

Figure 7. Japan AG1000 automatic grafting machine.

Research on active grafting began in Korea in the 1990s. In 2004, Helper Company developed GR-600CS grafting machine, as shown in **Figure 8**, which is similar to GR-800B grafting machine in Japan, and the grafting efficiency is 600 plants/h. Then it was improved to GR800CS automatic grafting machine, and the efficiency was increased to 800 plants/h. Ideal System (Korea) designed the solanum automatic grafting machine, as shown in **Figure 9**. The scion and rootstock are placed on the hole plate, and the grafting efficiency is up to 1200 plants/h.

**Figure 8.** Korean semi-automatic grafting machine.
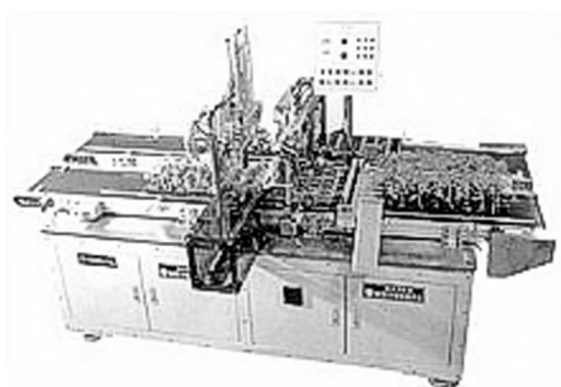
Figure 9. Korean automatic grafting machine.

For solanate crops, the automatic vegetable grafting machine developed by ISO Group of the Netherlands in 2009, as shown in **Figure 10**, adopts the flat grafting method; one person is needed for the root stock and one person for the scion. On this basis, the two types of grafting machines, ISO Graft 1100 and ISO Graft 1200, were changed into mechanical rootstock seedlings, and the grafting efficiency was up to 1000 plants/h.

Figure 10. Dutch eggplant grafting machine.

The vegetable grafting machine developed by the Spanish company CONIC SYSTEM, as shown in **Figure 11**, adopts the attaching method and is operated by one person. During operation, the graft machine cuts the stock and scion at 65°, and the automatic clamping port is set in the middle of the graft machine, where the operator only needs to dock the scion and the stock together, which is easy to operate[10–12].
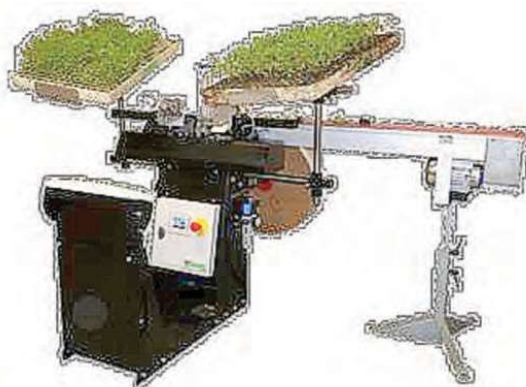
Figure 11. Spanish solanum vegetable grafting machine.

2.1.4. Transplant robot

In 2011, Kumar and Raheman[13] developed a vegetable transplanter for paper pot seedlings, which consists of two sets of conveyors (vertical conveyor, metering conveyor), feeding, and depth regulation. This machine is a double-row automatic vegetable transplanting machine, driven by a tractor. During the operation, 108 cave pan seedlings are transported to the metering conveyor by the vertical conveyor and planted vertically along the furrow. It was verified that the field production efficiency of the machine was 0. 026 hm^2/h, the operation speed was 0. 9 km/h, the transplanting efficiency was 32 plants/min, the leakage rate was 4%, the seedling rate was 95%, and the soil covering rate was 81%.

In 2012, a vegetable transplanting robot developed by Kang et al.[14] was composed of a transplanting mechanism, a flowerpot moving mechanism, a frame, a controller, etc. The transplanting part is composed of the detection mechanism and the actuator and is controlled by the photoelectric sensor and the servo motor. The movement of the four-finger pin manipulator is controlled by the controller (E-MY2H), which can accurately control the finger position. It has been proven that the optimal finger shape is a fine needle because it has the least damage to the root system of young agricultural engineering equipment and mechanized seedlings. The transplanting capacity is 2800 pots/h, and the success rate is above 99%.

In 2014, Zamani[15] studied the automatic tomato transplanting machine. This machine includes two parts: the mechanical structure and the control parts, which are composed of the chassis structure, seedling tray conveying mechanism, seedling taking mechanism, ditching apparatus, and PLC control system. During the operation, the hole plate conveying mechanism should proofread the position of the hole plate while doing the conveying action, and the seedling taking mechanism should accurately pick up the pot seedlings under the control of the PLC control system and accurately put them into the trench cutter to complete the transplanting operation.

2.1.5. Spraying robot

In 2009, the "Aigo" 3230 spraying machine developed by American Case Company, as shown in **Figure 12**, was suitable for medium-sized farms with smaller plots and higher flexibility[16]. The overall layout of the machine is reasonable, and the mass distribution is balanced, which can reduce soil compaction. The wet ground can be operated 1–2 days in advance. Its parameters are: the volume of the tank is 3028 L, the length of the spray rod is 27.4 m, the height of the spray is 48–213 cm, and the rated power is 161.7 kW (220 HP). The machine can be equipped with an AFS automatic navigation system to achieve automatic turning and an AIM command system to achieve constant pressure precision spraying within the range of 2–24 GPA. Three models of the Aigo series, the 3230, 4420, and 3330, have been promoted around the world.

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Figure 12. Case 3230 self-propelled spraying machine.

In order to improve operation efficiency, in 2014, John Deere Company improved and developed the 4630 self-propelled spraying machine based on the 4720 spraying machine, as shown in **Figure 13**[17]. The machine is equipped with a variable hydrostatic transmission system that can make hydraulic compensation according to the load-induced pressure and flow to ensure the pressure flow stability of the spray rod, walking motor, and other hydraulic components so as to control the spraying accuracy. The rated power is about 127 kW, with 3 spraying speed ranges, 1 transport speed range, and fertilizer spraying speeds up to 32 km/h. The ground gap is 1.32m, and the suspension stroke is 21 cm higher than before. At the same time, the Deere Green Star 2 Agricultural Production Management System (AMS) is equipped with automatic driving, guided spraying, and variable spraying.

Figure 13. John Deere 4630 sprayer.

In 2014, John Deere designed the new R4038 self-propelled spraying machine, shown in **Figure 14**, with a "field cruise" operation, rated at 228 kW[18]. The four wheels are equipped with an airbag shock absorption system, independent suspension, and an air cushion spring, which can automatically adjust the balance, and the wheel base can be adjusted in the range of 3048–3861 mm. With the Starfire RTK system, the accuracy was 2.54 cm. The capacity of the tank is 3785 L, the height of the nozzle from the ground is 684–2197 mm, the longest spray rod is 36 m, and the height of the nozzle from the spraying surface is 457–559 mm.

Figure 14. John Deere R4038 sprayer.

2.1.6. Picking robot

Japan began to study fruit and vegetable picking robots in 1980. Kawamura et al. developed a tomato picking robot by using the color difference between tomato fruits and background, as shown in **Figure 15**. Although the robot has five degrees of freedom and can perform three-dimensional positioning of fruits, it is still limited by space, and the mechanical claw is prone to damaging fruits[19]. Kondo N from Okayama University in Japan developed a tomato picking robot based on machine vision, which is composed of a walking mechanism, a vision system, a controller, and a manipulator. When working, the vision system can find and identify the ripe fruit, and the 7-DOF manipulator can effectively avoid obstacles to grasp. The manipulator is composed of two rubber fingers and a pneumatic suction nozzle. The suction nozzle will suck the fruit, and the manipulator will rotate to unscrew the fruit. The identification and picking efficiency of the machine was 15 s/piece, and the success rate was 70%. The reason for the low success rate of picking is that some ripe fruits are located in dense stems and leaves, and the manipulator cannot avoid picking them.

Figure 15. Tomato picking robot.

In 1996, the Netherlands Institute of Agricultural and Environmental Engineering developed an automatic cucumber harvesting robot consisting of a walking mechanism, a vision system, and a manipulator in order to hang cucumbers grown in greenhouses by winding a high-pull wire[20]. When working, the walking mechanism is equipped with a near-infrared vision system to find, identify, and locate ripe cucumber fruits and guide the 7-DOF manipulator to cut and pick them. It was proven that the working efficiency was 10 s/root, and the effect was good.

For the senryo-2 eggplant growing in a V-shape in the greenhouse, Japan's National Vegetable and Tea Research Institute and Gifu University jointly developed an eggplant picking robot, which consists of a

walking mechanism, a CCD machine vision system, and a manipulator[21]. During operation, the fuzzy vision system is used to identify ripe fruits and guide the robot to pick them. It has been verified that the picking efficiency of this machine is 64.1 s/piece, and the success rate reaches 62.5%. The fuzzy vision system's inaccurate judgment of picking positions and the long, time-consuming identification are the main reasons for the low picking efficiency and success rate.

2.2. Domestic research status

2.2.1. Agricultural information collection robot

A dual-purpose agricultural information collection robot designed by Wang et al.[22] of Northeast Forestry University is shown in **Figure 16**. Its flight control mechanism, ground-walking mechanism, and information collection system constitute a simple and practical agricultural information Internet of Things. The ground walking mechanism is equipped with an independent suspension and shock absorption system to enhance obstacle crossing ability and off-road performance. The aerial flight mechanism is equipped with a control system and an information acquisition system, and UAV technology is adopted to improve the ability of the robot to cross obstacles in the field. Through image acquisition, temperature and humidity detection, and image processing, the robot accurately obtains the temperature and humidity data of farmland and analyzes the growth status of crops. While obtaining reliable data and images, it provides a reliable basis for better management of farmland operations.

Figure 16. Ground and air dual-use information gathering robot.

Liu et al.[23] of Nanjing Agricultural University designed a small quadruped flexible robot for collecting agricultural information, which overcame the problem of soil mechanical compaction caused by large agricultural equipment. The robot adopts a small flexible quadruped robot structure, which is composed of a three-stage, two-degree-of-freedom leg structure, a remote rope-driven knee joint, and a spring energy storage device. The trajectory curve of the foot is inclined, which can improve the speed of the foot robot and reduce energy consumption.

2.2.2. Pruning robot

The core of the raspberry pruning robot designed by Meng and Liu[24] of China Agricultural University is a control system for serial communication between upper and lower computers. Based on machine vision technology, the robot establishes the color model and uses a variety of algorithms to process the collected images in real time. The left and right mechanical arms work simultaneously to realize the effective identification and efficient removal of thin and broken branches. At the same time, the machine has strong adaptability to complex environments, reliability, and adaptive ability.

Zhou et al.[25] from the University of Jinan designed a twin-wing rotary knife pruning machine for grape summer tips of hedge type, which is mainly composed of a cutting system, frame system, hydraulic system, and installation system, as shown in **Figure 17**. The cutting system is located on the left and right sides and the top of the robot, which is driven by the hydraulic system when working. It can trim the sides and top of two rows of grape frames at a time, and the ridge distance and height can be adjusted to realize a continuous,

efficient, and mechanized grape pruning operation and reduce the labor intensity and labor cost.
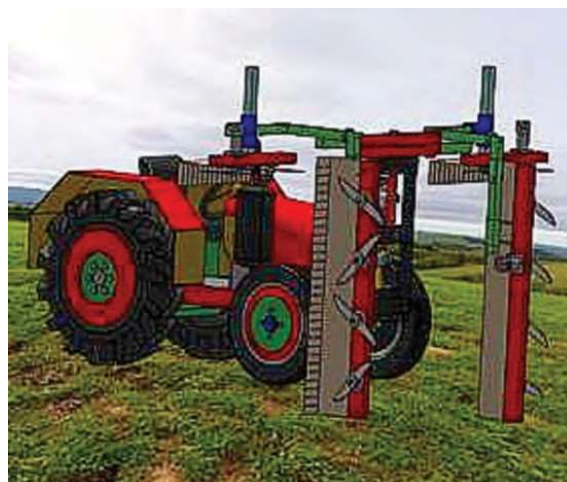

Figure 17. Grape summer pruning machine.

2.2.3. Grafting robot

Zhang et al.[26] of China Agricultural University took the lead in the study of vegetable grafting machines and developed the 2JSZ-600 single-arm hole disc grafting machine in 1988. This machine for melon vegetable seedlings, using the monocotyledon attachment method, rootstock can be directly grafted with soil, suitable for watermelon, melon, cucumber, and other vegetable seedlings, and has a wide range of adaptability. The grafting efficiency was 600 plants/h, but the success rate was only 95%. After that, the grafting efficiency of the improved double-arm graft was increased to 850 plants/h.

In 2006, Gu[27] of Northeast Agricultural University designed a 2JC-350 automatic grafting machine for vegetable grafting, which adopted a double-pin positioning mechanism to reduce the length of scion extension and ensure the quality of operation in the grafting link between rootstock and scion, thus effectively the grafting success rate. The production efficiency of the machine was 350 plants/h, but the grafting success rate was only 90%improving. In 2008, the grafting efficiency of the 2JC-600 graft machine was improved to 600 plants/h, and then it was optimized and improved to the 2JC-1000A full-automatic graft machine of Cucurbit. However, due to the intensive production and low degree of factory, the seedlings could not be mass-produced.

In 2011, Ma et al.[28] from South China Agricultural University put forward a new grafting method—automatic oblique grafting method with broken root and terminal bud—and developed a test bed for oblique grafting. The device consists of a stock holding mechanism, a stock socket mechanism, a scion holding transport mechanism, and a scion cutting mechanism. When working, the rootstock is held by the stock clamping mechanism to punch holes in the cuttings and keep them for a period of time. After scion cutting is completed, the cuttings are pulled out, and the scion is quickly inserted into the holes in the cuttings to complete grafting. The method and the device are simple, stable, and easy to popularize. The grafted seedlings are suitable for industrially intensive production, but the success rate of cutting reaches 92% and the survival rate of grafted seedlings reaches 90%.

For melons and solanum vegetables, the grafting robot designed by Jiang et al.[29] from Beijing Agricultural Intelligent Equipment Technology Research Center in 2011 based on the grafting technology of "attaching method" adopts pneumatic output and a PLC control system, which is mainly composed of a handling device, a cutting device, a seedling attaching device, and a clip feeding device. The Miao way to design the machine adopts double location: when the rotation radius of the cutter is 68 mm, the cutting speed is 120 r/min, the cutting seedling success rate is 98%, the grafting efficiency is 884 plants/h, and the and the

grafting success rate is 95.7%, which is close to factory grafting seedling production standards.

For cucurbitaceae hole tray seedlings, such as China Agricultural University's Chu[30], the design of the single operation grafting robot developed by a professor in tie-zhong zhang arms type vegetable grafting machines and 2 JSZ-600 type hole tray grafting machines is optimized on the basis of the improved operation efficiency, which can be improved by more than 50% per capita, grafting success rate can reach 95%, and grafting speed can reach 455 plants/h. However, the quality requirements of the cave disc seedlings are higher.

In order to improve grafting efficiency, in 2018 Tong and others from Zhejiang Sci-Tech University developed a joint-type semi-automatic vegetable grafting machine, which includes key components such as a clamping mechanism, a cutting mechanism and an anti-rotation mechanism, as shown in **Figure 18**. The machine is operated by a single person, and the seedling loading and clamping processes are coordinated in an orderly manner. The grafting success rate is 89%, and the grafting efficiency can reach 846.3 plants/h.
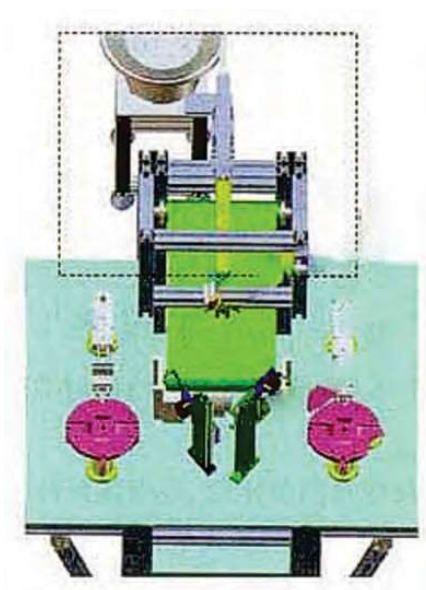
Figure 18. Single artificial seedling semi-automatic grafting machine.

2.2.4. Transplanting robot

In 2009, Zhou[31] of Nanjing Agricultural University designed a transplanting machine suitable for the transplanting of cave plate seedlings, which is mainly composed of a manipulator and a cave plate conveying system, etc., as shown in **Figure 19**. Its end-effector is an oblique wedge lever holding mechanism with a transplanting success rate of 76.11%. The operation time is 0.362 s shorter than the traditional way, and the efficiency is increased by 15.33%. The PLC control system is adopted, the vertical distance between fingers is 20 mm, and the best transplanting effect is achieved when the clamping force is about 3.877 N.
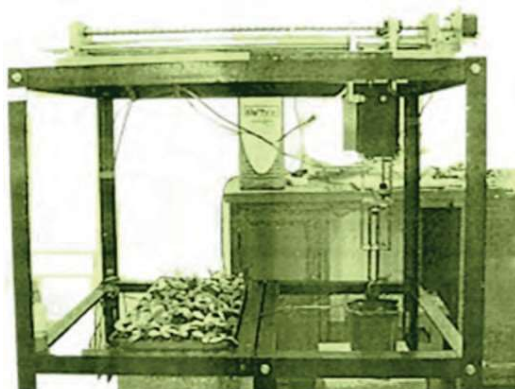
Figure 19. Greenhouse plug seedling transplanting machine.

In 2016, Han et al.[32] of Jiangsu University developed a light and simple automatic transplanting machine, which is mainly composed of an automatic transplanting manipulator and an electrical control system, as shown in **Figure 20**. The machine adopts a double-row chain drive, a mechanical arm including a linear module and roadless cylinder, and a and a manipulator for pneumatic two-finger, four-needle clamp type. It can complete the whole process of taking seedlings, transplanting seedlings, and planting seedlings. The success rate of transplanting was 90.70%, and the breakage rate was less than 5%. The transplanting efficiency of 128 and 72 hole disc seedlings was 1221 and 1025 plants/h, respectively.
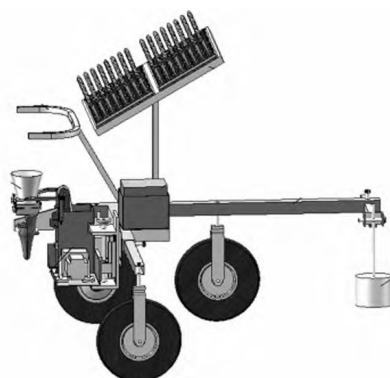

Figure 20. Lightweight automatic transplanting machine.

The matrix plant-vegetable transplanter designed by Cui et al.[33] in 2018 mainly consists of a power source, furrow opening and soil covering device, conveying and dividing seedling device, planting device and frame, etc. It can carry out the operations of bed surface leveling, furrow opening, transplanting, and soil covering at one time, as shown in **Figure 21**. During operation, the flat bottom roller compacted the soil, the trench opener opened the planting ditch, and the seedlings were manually taken and placed on the conveyor belt. The planter clamped the block seedlings for transplanting, and the soil coverer was covered and buried to complete the transplanting. The qualified rate of the transplanter was 95.3%, and the planting frequency was 57 plants/min.

Figure 21. Matrix seedling vegetable transplanter.

The light and simple semi-automatic transplanting machine designed by Zhao et al.[34] of Jiangsu University in May 2018 mainly consists of an electric chassis, a control system, seedling grafting and seedling mechanism, etc., as shown in **Figure 22**. The planting operation can be completed by a single driver, and the control system can control the start and stop of the transplanting machine and the speed control of the chassis. The operation is driven by a battery, the row spacing and plant spacing can be adjusted, and the speed will automatically match before the planting frequency is random. The plant leakage rate was 4%, the lodging rate was 6%, the variation coefficient of plant spacing was 4%, the qualified rate of planting was above 90%, and the qualified rate of planting depth was 82%.

Figure 22. Lightweight semi-automatic transplanter.

2.2.5. Spraying robot

In 2010, Modern Agricultural Equipment Technology Co., Ltd. and the China Academy of Agricultural Mechanization Sciences jointly developed the 3WZG-3000A high-clearance self-propelled boom sprayer for crops such as cotton, soybeans, and rapeseed, as shown in **Figure 23**[35]. The machine adopts a fully hydraulic four-wheel drive with a ground clearance of 1350 mm. It uses an air curtain airflow auxiliary device to prevent spray drift and is equipped with an automatic variable spray control system. Its working width is 21 m and the medicine tank capacity reaches 3000 L. The dosage is 150–600 L/hm^2; the working pressure is 0. 3–1.0 MPa, the operating speed is 6–10 km/h, the production efficiency can reach more than 8 hm^2/h, and the wheelbase can be adjusted within a certain range.

Figure 23. WZG-3000A sprayer figure.

To reduce pesticide-enhanced residues and reduce soil pesticide residues, Qingdao Agricultural University developed Guo et al.[36] in 2015, such as machine vision spraying Gu design such as the vegetable shed intelligent spraying robot, a robot mainly composed of the mobile platform, image acquisition and processing module, main control module, spraying module, and so on, as shown in **Figure 24**. The machine has Zigbee wireless communication and video transmission functions, which can realize unmanned and intelligent spraying operations. During the operation, the location and area of specific crops and weeds in the operation area were identified through image processing and analysis, and then the controller controlled the terminal spraying device to spray the target variety, that is, to spray herbicides and insecticides on weeds and crops, respectively.
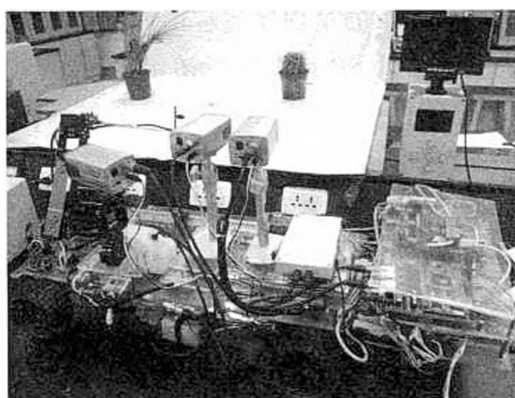

Figure 24. Machine vision spray robot.

In April 2018, Cao et al.[37] developed a remote control intelligent orchard spraying robot, which is mainly composed of a walking mechanism, liquid medicine supply and detection mechanism, atomization regulation mechanism, terminal spraying manipulator, image acquisition device, and terminal controller, as shown in **Figure 25**. The machine is driven by a motor, and the image acquisition device collects the site environment information in real time and transmits it to the controller so as to adjust the terminal spray manipulator to spray at a suitable angle and height. The maximum climbing angle is 33°, the operating speed is 5.65 km/h, the angle adjustment range of the terminal spray manipulator is 180°, and the spraying height is 1–3 m. The transmission distance of wireless control and video transmission can reach 200 m in an unobstructed environment. In a small occlusion environment, it still reaches 100 m.

Figure 25. Remote intelligent spray robot.

In order to improve the efficiency of the spraying robot for vegetable greenhouses, in August 2018, Gu et al.[38] designed the intelligent spraying robot for vegetable greenhouses, which is an all-in-one machine for watering, fertilization, and spraying. It is composed of a variety of sensors, controllers, image processors, and terminal execution arms. When working, the robot inspected along the "S" path in the vegetable greenhouse, and the image processing device detected the vegetable foliar lesions. The algorithm was used to make an intelligent ratio of the mixed solution concentration. The controller determined the spraying site and height, and finally, the spraying operation was completed by the end manipulator and spraying head. The robot can not only spray vegetables collectively but also spray with fixed point identification, realizing intelligent spraying and automatic inspection.

2.2.6. Picking robot

In view of the low efficiency of tree cone collecting, Lu[39] from Northeast Forestry University developed a tree cone collecting robot, which is mainly composed of a walking mechanism, a hydraulic drive system, a manipulator, and a single-chip computer control system. The machine adopts crawler walking mechanisms to ensure the reliability of moving in complex terrain. The 6-degree-of-freedom picking manipulator is driven by hydraulic pressure and controlled by a single-chip microcomputer system that can automatically and dynamically adjust different parent tree forms. It has been verified that the machine has a picking height of 14 m, a working radius of 6.8 m, a maximum gathering force of 2500 N, and a daily fruit collection of 500 kg, with an efficiency of 30–35 times that of manual.

In order to reduce the labor intensity and improve the intelligent level of cucumber picking, Ji et al.[40] of China Agricultural University developed a greenhouse cucumber picking robot, which is mainly composed of a PTZ camera, an on-board industrial computer, a motion controller, and crawler parts, as shown in **Figure 26**. The robot is controlled to walk by the automatic navigation control system, and picking is controlled by the automatic picking system based on visual recognition. It has been verified that the continuous working time of the machine is 2 h, the forward speed is 0.3 m/s, and the navigation accuracy is 5 mm. However, the picking success rate is 85%, and the single root picking time is 28.6 s.

Figure 26. Greenhouse cucumber picking robot.

A tomato-picking robot designed by Zhou et al.[41] of Qingdao University of Technology uses a raspberry Pi 3B controller and binocular camera to identify and position the fruit so as to control the robot arm to pick tomatoes. The verification shows that the target recognition success rate of this machine is 78%, and the single picking time is less than 15 s. However, it is susceptible to the influence of environmental light factors, resulting in a decrease in the accuracy of recognition results. At the same time, leaf shading and fruit overlap will also cause inaccurate recognition.

In view of the orchard under the dwarfing and dense planting cultivation mode, Gao et al.[42] of Jiangsu University designed a 4-DOF lifting-type picking robot, which is mainly composed of a moving mechanism, a scissor lifting mechanism, a picking robot arm, an extractable fruit box, and a real sense vision sensor, as shown in **Figure 27**. The machine adopts a miniaturized design to adapt to the orchard cultivation mode. At the same time, the robot arm can enter the canopy of the fruit tree to pick the target fruit reasonably and reduce the degree of freedom of the robot arm. Due to joint clearance and elastic deformation of materials, the control error of the single joint position of the machine is 1.06–3.02 mm, which basically meets the operation requirements.

Figure 27. Small lift picking robot.

3. Key technologies of agricultural robots

Although many breakthroughs have been made in agricultural robot technology, the working environment and objects of agricultural robots are complex and changeable, and some key technologies are not mature. The development of agricultural robots still faces challenges.

3.1. Autonomous navigation technology

Autonomous navigation has become the main way for agricultural robots to travel. Relying on autonomous navigation technology, agricultural robots can achieve intelligent operations such as fertilization, spraying, and weeding. At present, the navigation technologies mainly include GPS navigation, machine vision navigation, ultrasonic navigation, laser navigation, and crop row navigation, among which machine vision navigation has gradually become the main mode of agricultural robot navigation. The autonomous navigation technology first locates the robot itself. On this basis, the agricultural robot plans the path, predicts the land head, and turns the land head. The application of autonomous navigation technology in agriculture is a development trend that is conducive to the large-scale and standardized operation of agriculture in the future[43,44].

3.2. Autonomous obstacle avoidance technology

In recent years, China's machinery automation, computer control systems, and other industries have developed rapidly. The development of science and technology in agriculture is intended to improve the level of agricultural intelligence. How to avoid obstacles from agricultural robots is a classic problem. Autonomous obstacle avoidance technology requires that the robot not touch the obstacles when moving to the destination. The obstacle avoidance ability depends on the intelligent level of the robot, which is manifested in two aspects: environmental sensing and path planning, namely, path finding and obstacle avoidance. The existing obstacle avoidance algorithms mainly include the ant colony algorithm, Hopfield, differential evolution algorithm, genetic algorithm, BP neural network, and artificial potential field. The complex and diverse working environment in farmland has higher requirements for the autonomous obstacle avoidance ability of agricultural robots[45,46].

3.3. Multisensory information fusion technology

Multi-sensor information fusion technology integrates the technologies of control theory, signal processing, and artificial intelligence, which can accurately reflect the characteristics of the detected object and improve the reliability of information. Multi-sensor information fusion technology is gradually applied to the field of agricultural robots (precision agricultural technology, monitoring of agricultural resources and agricultural environment, monitoring of production processes, etc.), providing a solution for agricultural robots to work in complex and dynamic environments[47,48].

3.4. Agricultural robot end effector

China's fruit and vegetable production ranks among the top in the world, but the picking process is mainly completed manually, which is time-consuming, labor-consuming, and costly. Therefore, it is of great significance to develop an agricultural robot end effector that can carry out efficient and low-loss picking. The performance of the end effector has a direct impact on the picking effect. At present, the main factors affecting the picking effect include picking accuracy, picking speed, adaptability of the working environment, and universality. Traditional rigid manipulators have problems such as insufficient control accuracy, poor versatility, and picking damage. Developing soft manipulators to realize flexible picking is the development trend of agricultural robot end effectors[49,50].

4. Existing problems

1) Agricultural robot operation technology in a dark night environment. At present, robots can only work during the day, and the robot does not know the characteristics of fatigue. The fruit recognition technology based on infrared light and multispectral should be further studied to improve fruit resolution and maturity

discrimination efficiency in a light-deficient environment so as to realize the all-weather picking operation.

2) Robot group operation technology. The farmland production environment is complex, and the terrain is irregular. A single robot is equipped with a complete set of information monitoring systems and job execution systems, which will lead to high machine complexity. Therefore, the joint operation technology of multiple robots should be studied, and different monitoring and execution equipment should be equipped to realize the joint operation.

3) Fruit position determination and obstacle avoidance harvesting techniques. It is necessary to further study the fruit identification and actuator obstacle avoidance and clamping technology based on artificial intelligence to solve the problem of leaf and branch occlusion and study the nondestructive harvesting method of fruit. The technology of human-machine combined harvesting is studied, and the implementation mechanism completes the operation under the decision of humans so as to reduce the design difficulty.

4) Accompanying robot problem. In view of the current agricultural situation in China, it may be a transitional method in line with China's national conditions to design accompanying robots to assist people in completing complicated transplanting and grafting operations, to realize semi-automatic production of protected agriculture, and to reduce labor intensity.

5. Concluding remarks

The research of agricultural robots in foreign countries started early, the technology was perfect, and various models developed comprehensively, but most of them have not reached the industrialization level. In addition, most foreign models have complex structures and high costs, so they can't adapt to the agricultural characteristics of China. Domestic agricultural robot research started late, but related industries developed rapidly. Researchers have done a lot of useful research work and developed a variety of models, but most of them are in the theoretical development stage. The development of new technology and the improvement of agricultural production demand put forward higher requirements for agricultural robots. In the 21st century, with the support of big data, artificial intelligence, sensors, and other technologies, agricultural robots need to constantly improve their intelligence level in order to better serve agriculture and catch up with the international level.

Conflict of interest

The authors declare no conflict of interest.

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