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Review

Review and Prospect for Vegetable Grafting Robot and Relevant Key Technologies

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Abstract: Grafting is an effective way to overcome the obstacles of continuous soil cropping and improve the tolerance of plants to abiotic and biotic stresses. An automatic grafting robot can effectively improve the grafting efficiency and survival rate of grafted seedlings, which is an important demand for the commercialization and promotion of vegetable planting. Based on the six main grafting technologies, this paper deeply summarized and analyzed the research status, technical characteristics, and development trends of vegetable grafting robots developed by various countries in the world. At the same time, it focused on the design methods and characteristics of key components such as seedling picking device, clamping device, and cutting device of vegetable grafting robots in detail. Then, the application of machine vision in the grafting robot was compared from the aspects of seed information feature recognition, automatic seedling classification, seedling state detection, and auxiliary grafting. It also was pointed out that machine vision technology was the only way to realize the fully automated grafting of vegetable grafting robots. Finally, several constraints, such as the limited grafting speed of vegetable grafting robots were pointed out, and the future development direction of grafting robots was predicted. As a result, it is believed that the intelligence degree of vegetable grafting robots needs to be improved, and its research and development fail to integrate with the seedling biotechnology, which leads to its poor universality. In the future, improving machine vision, artificial intelligence, and automation technology will help the development of high-performance universal grafting robots.

Keywords: vegetable grafting robot; feature recognition; seedling classification; development status

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1. Introduction

With the improvement of people's living standards, the increasing requirements for vegetables have promoted the rapid development of vegetable factory seedling breeding and also brought about the problems such as vegetable diseases and insect pests. Vegetable grafting techniques are the most effective means to solve these problems. Grafting is a method of asexual propagation in which a branch or bud of one plant (i.e., scion) is combined with another plant (i.e., rootstock) with strong affinity so that the two parts are joined together to become a complete and independent plant. Basically, the improvement of fruit yield and the quality of horticultural crops, the overcoming of continuous cropping obstacles, the tolerance of plants to abiotic stress, and the utilization efficiency of mineral nutrients can be realized by grafting [1].

Since the 1980s, researchers have conducted a quantity of research on vegetable grafting robots. Japan was the first to study the grafting robot. Korea began to study vegetable grafting robots in the early 1990s. So far, they have launched semi-automatic grafting robots that are relatively mature and suitable for their national development [2]. In addition, China began research on vegetable grafting robots in 1993. As representatives, Zhang and Gu have developed mature semi-automatic grafting robots, which are currently being developed toward full automation [3]. In Europe [4], some agriculturally developed countries also carried out vegetable grafting robot research at the beginning of the 21st century and made some achievements, such as The Netherlands, Italy, Spain, and so on.

With the continuous expansion of vegetable cultivation areas and the increasing demand for grafted seedlings, much more labor is needed for grafting, resulting in an increase in the cost of seedlings [5]. To solve these problems, the grafting robot is invented. In fact, the grafting robot can reduce the working intensity and improve grafting productivity. At present, the design of the key grafting devices of the vegetable grafting robot is mainly concentrated in the seedling, clamping and cutting device, and gradually develops towards refinement and automation. Since the implementation of fully automated grafting operations of the grafting robot depends on the correct identification of work objects, the application of machine vision technology can make the entire grafting process more automated. For example, the automatic grading of seedlings before grafting can solve the problem of matching the diameter of different rootstocks and scions. With the development of information technology, automation and intelligence are the only ways to the development of grafting robots, such as the construction of automatic grafting supporting production systems and the development of intelligent human-computer interaction systems. In addition, the quality assessment and grafting prediction of grafted seedlings by combining machine vision and artificial intelligence and the development of high-efficiency grafting robots are the directions of future development.

2. Development of Vegetable Grafting Robot

At present, the main vegetable grafting techniques include splice grafting, tube grafting, insertion grafting, approach grafting, pin grafting, and cleft grafting. Researchers in various countries have developed various grafting robots with different grafting methods. The commonly used methods of vegetable grafting are shown in Figure 1.

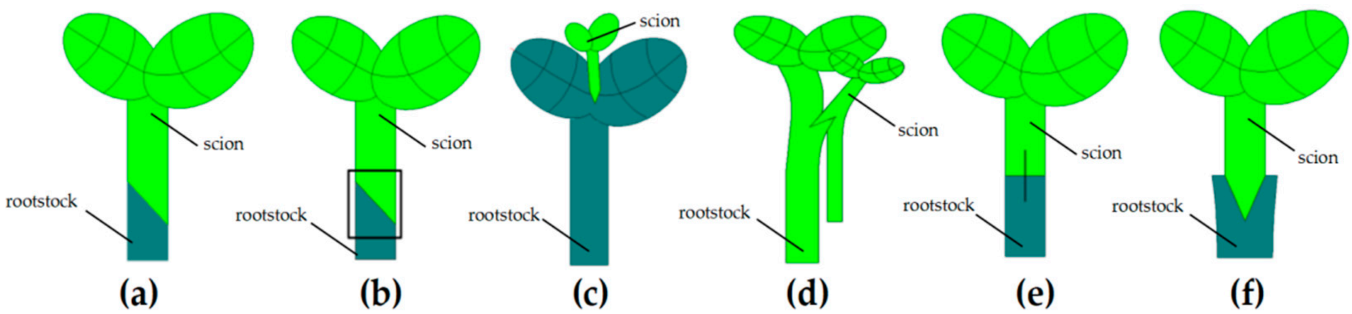

Figure 1. Common grafting methods for vegetables. (**a**) Splice grafting; (**b**) Tube grafting; (**c**) Insertion grafting; (**d**) Approach grafting; (**e**) Pin grafting; (**f**) Cleft grafting.

2.1. Research and Development of Vegetable Grafting Robot Based on Splice Grafting

Splice grafting is mainly used for grafting solanaceous and cucurbit vegetables. During the grafting process, the tip of the rootstock and the bottom of the scion is cut into slanted surfaces with a blade; then the two slanted surfaces are tightly joined and fixed to form grafted seedlings.

In 1994, Japan ISEKI company launched the GR800 series vegetable grafting robot. In the grafting robot, one way of feeding seedlings on the gap bracket is adapted to fix the rootstock and the scion seedling with a productivity of 800 plants/h and a survival rate of 95%. In 2011, the ISEKI company also launched the GRF800-U automatic grafting robot [6].

In the robot, an automatic seedling feeding device based on the hole-plate was developed, which could replace the artificial seedling feeding operation. In addition, the grafting robot has a high degree of visualization, and workers can operate it through a touch screen. In 1994, Japan Yanmar company developed AG1000 series automatic grafting robot for solanum vegetables [7]. During the grafting process, the transportation, clamping, cutting, and docking of rootstocks and scions could be accomplished by three conveyor belts, and six seedlings could be grafted at the same time, but the quality of grafted seedlings was easily affected by the plant height and stem diameter. In 2010, Conic Systems Company in Spain developed an EMP 300 single-operation semi-automatic grafting robot with silicone clips [8]. Some mechanisms of the grafting robot for the operation of clamping and cutting, and docking were arranged symmetrically, which ensured the consistency of the cutting angle and the accuracy of the incision docking. However, the grafting speed of the grafting robot was only 400~600 plants/h, which was not efficient and only suitable for small seedling enterprises.

China started research on vegetable grafting robots in the 1990s. In 1998, Zhang et al. from China Agricultural University launched the 2JSZ-600 single-arm automatic vegetable grafting robot for cucurbit vegetables, which could perform multiple processes such as picking, cutting, joining, fixing, and rowing seedlings [9]. Its grafting speed was 600 plants/h. In 2009, the team launched the 2JSZ-600B double-arms bidirectional vegetable grafting robot [10]. They adopted a bidirectional grafting mechanism: the rootstock and scion seedlings could enter the cutting mechanism from the left and right directions at the same time, and the grafting speed reached 854 plants/h. In 2011, the TJ-800 vegetable automatic grafting robot was developed by the National Agricultural Intelligent Equipment Engineering Technology Research Center of China [11]. They adopted the operation mode of double-station feeding seedlings, and the robot was equipped with clamping hands and cutting devices for the rootstock and scion, respectively. The productivity reached 800 plants/h, and the survival rate reached 95%. In 2014, Chu et al. from China Agricultural University designed a single-person grafting robot for cucurbit pot seedlings [12]. The robot was designed with an automatic arrangement and placement mechanism for grafting pot seedlings. A single worker can complete the seedling supply. Compared with the same type of double seedling grafting robots, the per capita work efficiency was increased by 36%. In 2015, Beijing Agricultural Information Technology Research Center and Beijing Agricultural Intelligent Equipment Technology Research Center jointly launched a solanaceous vegetable grafting robot [13]. It achieved the rapid operation of one worker by way of horizontal seedling supply and linear sliding cutting. Its average production efficiency was 512 plants/h, and the survival rate of grafted seedlings was 99.5%. In 2020, Liu et al. from South China Agricultural University developed a semi-automatic grafting robot for solanaceous fruit seedlings based on the assembly line [14]. In the robot, the six processes of clamping, cutting, gathering seedlings, docking, clip sending, and seedling taking were divided into four working stations. Its grafting rate could reach 1000 plants/h, which greatly improved the operation speed.

In 2021, Hefei Jiafute Robot Technology Co., Ltd. developed a semi-automatic vegetable grafting robot with the model JFT-A1500T. The grafting robot can flexibly assemble multiple grafting robots into a production line to meet different production requirements, and its maximum grafting speed is 1500 plants/h, as shown in Figure 2. In 2022, Fu et al. from Huazhong Agricultural University designed a full-tray grafting robot for splice-grafted cucurbit crops, as shown in Figure 3 [15]. The characteristics of each robot are shown in Table 1.

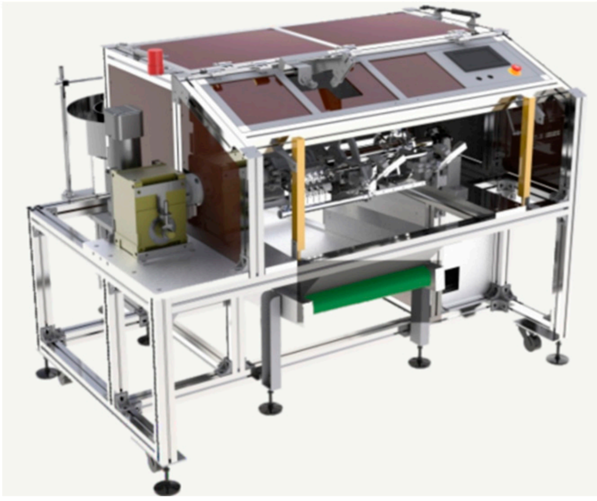

Figure 2. JFT-A1500T semi-automatic grafting robot developed by Hefei Jiafute Robot Technology Co., Ltd.

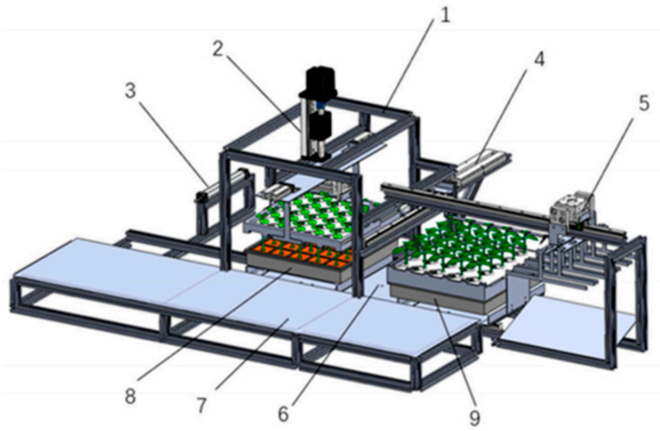

Figure 3. HAU-22 fully automatic grafting robot developed by Huazhong Agricultural University: 1. Rack; 2. Clamping-lifting device; 3. Seedling-lowering device; 4. Synchronous-cutting device; 5. Clamping and transferring device for the upper half of the rootstock seedlings; 6. Plug tray-positioning device; 7. Upper seedling platform; 8. Scion-seedling plug tray; 9. Rootstock-seedling plug tray.

2.2. Research and Development of Vegetable Grafting Robot Based on Tube Grafting

In the tube grafting, scions and rootstocks with similar seedling diameters are selected to cut and fit, and they are connected by some special plastic casings.

Japanese researchers have made a lot of useful attempts in the development of vegetable grafting equipment based on tube grafting and achieved some good results. In 1992, the Japanese Mitsubishi Group developed an MGM600 automatic grafting robot (Mitsubishi Group, Tokyo, Japan) for the Japanese Agricultural Cooperative Union, as shown in Figure 4 [16]. Based on the grafting mode of nutrition bowls, a single row of pot seedling delivery devices was developed through the conveyor belt, which could accurately transport seedlings to seedling feeding stations. In fact, there is a large amount of transportation and a high matching degree of rootstock and scion in this grafting mode. In 2003, the Japanese Yanmar company developed a T600 semi-automatic vegetable grafting robot, which could automatically complete cutting, docking, fixing, casing, and other operations of rootstocks and scions on the seedling fixing rack with only one worker [17].

Table 1. Comparison of the characteristics of the vegetable grafting robots based on splice grafting.

Time	Model	Research Unit	Suitable Object	Productivity (Plants/h)	Survival Rate	Automaticity
1994	GR800	ISEKI, Japan	Melon and Solanaceae vegetables	800	95%	Semi-automatic
1994	AG1000	Yanmar, Japan	Solanaceae vegetables	1000	97%	Full-automatic
1998	2JSZ-600	China Agricultural University	Melon vegetables	600	95%	Semi-automatic
2009	2JSZ-600B	China Agricultural University	Melon and Solanaceae vegetables	854	95%	Full-automatic
2010	EMP300	Conic System, Spain	Solanaceae vegetables	400~600	98%	Semi-automatic
2011	TJ-800	**1**	Melon and Solanaceae vegetables	800	95%	Semi-automatic
2011	GRF800-U	ISEKI, Japan	Melon vegetables	800	95%	Full-automatic
2014	**2**	China Agricultural University	Melon vegetables	440	92%	Full-automatic
2015	**3**	**4**	Solanaceae vegetables	512	99.5%	Automatic
2020	**5**	South China Agricultural University	Solanaceae vegetables	1000	-	Semi-automatic
2021	JFT-A1500T	**6**	Melon and Solanaceae vegetables	1500	98%	Semi-automatic
2022	HAU-22	Huazhong Agricultural University	Melon vegetables	2134	67%	Full-automatic

Note: **1**—National Engineering Research Center for Agricultural Intelligent Equipment (NERCIEA), National Engineering Research Center for Information Technology in Agriculture; **2**—Cucurbit pot seedling single operation Grafting robot; **3**—Solanum vegetable grafting robot; **4**—Beijing Research Center for Information Technology in Agriculture; **5**—Solanum vegetable semi-automatic grafting robot; **6**—Hefei Jiafute Robot Technology Co., Ltd.

Figure 4. MGM600 semi-automatic grafting robot developed by Mitsubishi Group.

Dutch researchers have also tried a lot. In 2007, The Netherlands ISO Group company developed the Graft1000 automatic grafting robot (ISO Group, Gameren, The Netherlands) with an information image recognition system and conveying system of seedlings, which could complete the matching and grafting of rootstocks and scions. In 2010, it developed a Graft1200 automatic grafting robot [18]. In the robot, a single-opening silicone casing clip was used to replace natural rubber hoses, and the automatic transmission of silicone clips was simplified. Besides, the robot could be operated by a single worker, and the height of feeding seedlings could be determined by a laser emitter. The above two robots had a high degree of automation but were more expensive. In 2014, to reduce the sales price, the company again developed a Graft1100 semi-automatic grafting robot with 1000 plants/h productivity and a 98% grafting survival rate, as shown in Figure 5 [19]. In 2016, China Agricultural University designed a tube-outputting device for a vegetable grafting robot using the tube-grafting method. The device comprises vibration sorting-tube device, a tube duct, and a tube one-by-one delivery unit. The success rate of the device is 100%, which can fully ensure the tube supply for subsequent grafting operations [20]. The characteristics of each robot are shown in Table 2.

Figure 5. Graft1100 semi-automatic grafting robot developed by ISO Group.

Table 2. Comparison of the Characteristics of the vegetable Grafting robots Based on Tube Grafting.

Time	Model	Research Unit	Suitable Object	Productivity (Plants/h)	Survival Rate	Automaticity
1992	MGM600	Mitsubishi Group, Japan	Solanaceae vegetables	600	95%	Semi-automatic
2003	T600	Yanmar, Japan	Melon vegetables	600	98%	Semi-automatic
2007	Graft1000	ISO Group, Netherlands	Solanaceae vegetables	1000	99%	Full-automatic
2010	Graft1200	ISO Group, Netherlands	Melon and Solanaceae vegetables	1050	99%	Full-automatic
2014	Graft1100	ISO Group, Netherlands	Melon and Solanaceae vegetables	1000	98%	Semi-automatic
2016	**1**	China Agricultural University	-	-	-	Full-automatic

Note: **1**—tube-outputting device of Vegetable grafting robot.

2.3. Research and Development of Vegetable Grafting Robot Based on Insertion Grafting

In the insertion grafting, one cut scion seedling is inserted directly into the growth point of the rootstock to form a new grafted seedling.

In 2005, Professor Gu et al.'s team from Northeast Agricultural University developed a 2JC-350 plug-in semi-automatic melon vegetable grafting robot, as shown in Figure 6. In the robot, the rootstock and the scion seedlings were conveyed manually. The power was transmitted through the mechanical cam to complete the operation such as the clamping of the rootstock, the removal of the growth point of the rootstock, the punching of the rootstock, the clamping of the scion, the cutting of the scion, and the docking between the scion and the rootstock [21]. Subsequently, 2JC-450, 2JC-500, and 2JC-600 grafting robots were developed based on the 2JC-350 grafting robot, and the grafting rate gradually increased to 600 plants/h [22–24]. In 2010, South China Agricultural University cooperated with the National Agricultural Intelligent Equipment Engineering Technology Research Center to develop the 2JC-1000A automatic grafting robot [25]. In the grafting robot, two robotic arms were designed to graft five seedlings at the same time with 1000 plants/h grafting speed. In 2011, South China Agricultural University designed an automatic grafting robot for the oblique insertion of melons. The grafting robot adopts oblique grafting instead of direct grafting to solve the problem of graft failure caused by a scion inserted into the pulp cavity of rootstock. The grafting success rate of the machine can reach 95%, and the productivity is higher than 600 plants/h [26]. In 2020, Guangdong Mechanical and Electrical Polytechnic and Beijing Research Center of Intelligent Equipment for Agriculture jointly designed a visually guided robot for watermelon grafting based on insertion grafting. The robot uses machine vision to recognize and locate the rootstock and scion then accurately punch the hole to insert the watermelon scion into the hole [27]. The characteristics of each robot are shown in Table 3.

Figure 6. 2JC-350 plug-in semi-automatic grafting robot developed by Northeast Agricultural University.

Table 3. Comparison of the Characteristics of the Vegetable Grafting Robots Based on Insertion Grafting.

Time	Model	Research Unit	Suitable Object	Productivity (Plants/h)	Survival Rate	Automaticity
2006	2JC-350	Northeast Agricultural University	Melon vegetables	350	>90%	Semi-automatic
2009	2JC-450	Northeast Agricultural University	Melon vegetables	450	>90%	Semi-automatic
2009	2JC-500	Northeast Agricultural University	Melon vegetables	500	>90%	Semi-automatic
2010	2JC-1000A	**1**	Melon vegetables	1000	>90%	Full-automatic
2011	2JC-600	Northeast Agricultural University	Melon vegetables	600	>90%	Automatic
2011	**2**	South China Agricultural University	Melon vegetables	600	95%	Semi-automatic
2020	**3**	**4**	Melon vegetables	-	95.6%	-

Notice: **1**—South China Agricultural University and National Agricultural Intelligent Equipment Engineering Technology Research Center; **2**—oblique insertion automatic grafting robot; **3**—Visual-guided vegetable grafting robot; **4**—Guangdong Mechanical and Electrical Polytechnic and Beijing Research Center of Intelligent Equipment for Agriculture.

2.4. Research and Development of Other Vegetable Grafting Robots

Korea began to study vegetable grafting robots in the early 1990s. The Korea Helper Robotech company launched one AFGR-800CS supreme precision grafting robot, as shown in Figure 7 [28]. The grafting robot used the real-time acquisition system of seedling section information to take real-time photos of the cross-section of the rootstock and scion, which could ensure the accuracy of grafting incision alignment. As a result, the grafting rate could reach 800 plants/h, and the grafting survival rate was at least 95%. It was designated as a world-class product by the Korean government in 2013. In 2004, the Korea Ideal System company developed a needle-connected automatic grafting robot based on pin grafting [29]. In the robot, a pentagonal-shaped ceramic needle was inserted into the stem of the rootstock and the scion through the needle insertion mechanism, which could make the cut surfaces of the rootstock and the scion closely fit and prevent the grafting part from rotating. Finally, the grafting was accomplished with a 1200 plants/h grafting rate and 95% grafting survival rate. However, it is difficult to ensure the tightness and stability of the section surfaces of grafted seedlings, and it has not been verified in the actual production. In 2018, China Qingdao Agricultural University and Shandong Zhongtianshengke Automation Equipment Co., Ltd. jointly launched the JS-6 vegetable grafting robot, which could achieve synchronous automatic cutting and grafting of six rootstocks and scion seedlings and improve the grafting rate [30]. The characteristics of each robot are shown in Table 4.

Figure 7. AFGR-800CS supreme precision grafting robot developed by Helper Robotech.

Table 4. Comparison of the Characteristics of Other Vegetable Grafting robots.

Time	Model	Research Unit	Grafting Technology	Suitable Object	Productivity (Plants/h)	Survival Rate	Automaticity
2004	**1**	Ideal System, Korea	Pin grafting	Solanaceae vegetables	1200	95%	Full-automatic
2013	AFGR-800CS	Helper Robotech, Korea	Approach grafting	Melon and Solanaceae vegetables	800	95%	Full-automatic
2018	JS-6	**2**	Cleft grafting	Solanaceae vegetables	720	96%	Full-automatic

Notice: **1**—needle-connected automatic grafting robot; **2**—Qingdao Agricultural University and Shandong Zhongtianshengke Automation Equipment Co., Ltd.

As a result, according to the different types of vegetable seedlings and grafting technology, researchers in various countries have successfully developed different types of grafting robots. During the research process, the development of grafting robots is also developing from semi-automation to full automation, and production efficiency is also gradually improving. Since grafting robots are developed in accordance with agricultural production, their development is inseparable from the research related to biological science and agronomy. According to the current research progress of grafting robots, it is relatively easy to operate for splice grafting, in which the top of the rootstock and the bottom of the scion only need to be cut for fitting and fixing. In addition, some modern mechanical structures adopted in the splice grafting method are easy to be completed and can also achieve a large area of automatic production, so the main research and development direction is about the vegetable grafting robot based on the splice grafting method. However, due to the excessive manual operation and complicated design, insertion and tube grafting are not conducive to automation and fine control, so there are few achievements in grafting structure research.

3. Design of Key Parts and Components of the Vegetable Grafting Robot

The vegetable grafting robot comprises some kinds of devices such as seedling feeding, clamping, cutting, rootstock and scion docking, seedling picking, and a control system, which can complete the entire grafting operation. As a grafting device, its design conforms to the design process of general equipment. According to the use function and process, the comprehensive design is mainly carried out from four aspects: seeding feeding, clamping, cutting, rootstock and scion docking, and seeding picking, specifically involving market research, preliminary scheme design, detailed design, control system, testing, prototype optimization, batch production, and other links. In the process of grafting, the control system controls the operation of each device, generally based on PLC or Single-Chip Microcomputer as the core; the technology has been quite mature. At present, the research mainly focuses on the research of the seedling feeding device, the clamping device, and the cutting device.

3.1. Design of the Seedling Feeding Device

At present, manual seedling feeding is generally adopted in vegetable grafting robots, so the research on the mechanical delivery of seedlings has become a research focus. The 2-PPA parallel mechanism was designed in the automatic seedling feeding device by Wang, Xiang, and Shen et al. [31–33]. Xiang established the kinematic equation based on the parallel mechanism model, optimized the sizes, and analyzed the accuracy of the mechanism according to the comprehensive performance index. In the end, the maximum error of the end effector in the system was 0.12 mm, which ensured the accuracy of seedling feeding. Similarly, based on this parallel mechanism, Wang designed an automatic seedling feeding device that fulfilled the functions such as automatic seedling supply, clamping and picking, seedling feeding and positioning. The expected effect was achieved through one practical experiment. Due to the popularity of small grafting robots, more useful functions of the seedling feeding device have been developed and widely used. Song [34] designed an automatic seedling feeding device, which could complete intelligent grading before automatic seedlings supply. The device was composed of three parts: an automatic seedling feeding device for rootstocks, an automatic seedling feeding device for scions, and an intelligent grading optional storage device, which could complete the grading operation before seedling feeding. Pan [35] designed a seedling feeding device that could cut the roots of grafted seedlings. Through the cooperation between the combined screw-sliding rods and the end effector with the function of clamping broken roots and cutting, the device could achieve functions such as seedling clamping, cutting broken roots, and lateral transportation of seedlings. Besides, some optimization of seedling feeding devices has also been done. Aiming at the lack of an automatic seedling feeding device in the 2JT-1600 type solanaceous fruit grafting robot, Peng et al. [36] added a conveying chain and a transfer mechanism for grafting seedlings in the rootstock and scion seedling delivery stations, respectively, so that the rootstock and scion could be delivered to the seedlings by one worker. Moreover, a seedling feeding clip with better seedling picking performance was also developed, and the seedling picking error is within 5 mm.

3.2. Design of the Clamping Device

In the grafting robot, the clamping mechanism is mainly used to pick, handle and correct the bending degree of the seedlings, and fix and assist the seedlings in completing the cutting and connection, which plays an important role in the speed rate and success rate of grafting. Jiang et al. and Lou et al. [37,38] designed a clamping mechanism with adjustable clamping force. The clamping part designed by Lou et al. adopted the way of cross-clamping between convex and concave clamping pieces, which could adjust the clamping force through the tightness change of the spring. The clamping mechanism designed by Jiang et al. precisely controlled the clamping force of the seedlings by adjusting the clamping distance of the buffer pad. In addition, the buffer material of the clamping could achieve the flexible clamping of the seedlings. Yang et al. [39] and Chu et al. [26] accomplished the clamping action with pneumatic cylinders. The clamping mechanism designed by Yang et al. achieved the closure of the gripper by driving the Y-shaped cylinder. In the clamping mechanism designed by Chu et al., the moving clamps on the rootstock were driven pneumatically toward the static clamp so as to complete the clamping action. Besides, a vacuum suction hole was designed at the edge of the clamp to absorb and flatten the cotyledons. Considering that the grafting robot should be adapted to seedlings with different stem thicknesses, Li et al. and Jiang et al. [40,41] designed a detachable seedling clamping mechanism. The operator could replace the chuck to complete the grafting operation according to the thickness of the seedling stem. The structure of the rootstock clip designed by Li et al. adopted the combination scheme of "integral clip body, independent collet," enabling five clips to work at the same time, which could accomplish the rapid grafting of five seedlings synchronously. The optimization of the clamping mechanism can further improve the clamping efficiency. Xia et al. [42] used SolidWorks software to find the weak parts in the end effector of the transplanting manipulator. They achieved the optimization of the end effector by changing the structure and sizes of the connecting rod and soil excavator. The air suction clip of rootstock cotyledons designed by Yang et al. [43] spread the cotyledons of the rootstock into a plane. It adsorbed them on the surfaces of the rootstock clip through suction operation, which could replace the traditional seedling pressing mechanism.

3.3. Design of the Cutting Device

In vegetable grafting, the performance of the cutting mechanism directly affects the speed and survival rate of grafting. The cutting mechanisms designed by Li et al. and Xu et al. [44,45] adopted the way of rotary cutting to cut rootstock and scion. The cutting mechanism designed by Li et al. could accomplish the cutting of the rootstock and scion utilizing the semi-rotational motion of the cutter and the cutter rod driven by the rotation of the cam. Xu et al. designed one cutting mechanism to achieve the simultaneous cutting of the rootstock and scion by way of driving the cutter frame to rotate with a rotating cylinder. In the cutting mechanism designed by Liang et al. [46], the method of transverse sliding cutting was adopted to accomplish the cutting of the scion. As a good structure, the needle cylinder drives the tool holder to move the cutter along the direction of the tool groove. The cutting mechanism designed by Tang et al. [47] could realize the precise adjustment of the upper, lower, and front positions of the cutter in the X direction and Y direction. Optimizing the cutting mechanism can improve the cutting efficiency and ensure a better cutting effect. Researchers have carried out a lot of experiments on this, mainly focusing on optimizing the cutting structure and cutting parameters. In the end, some good optimization results were achieved. Li et al. and Tian et al. [48,49] optimized the working parameters of the cutting device. Li et al. determined the optimal parameters of the cutting device by observing the cutting offset rate of the seedling stem and the drawing rate of the stem. In contrast, Tian et al. determined the optimal working parameters by analyzing the single factor experiment and carrying out the quadratic regression orthogonal experiment on the cutting parameters. In terms of structural optimization, Bai et al. [50] used multiple cutting blades parallel to replace the reciprocating cutting mechanism to accomplish the cutting of a whole row of vegetable seedlings in the plug tray.

As shown in Table 5, the design direction of key parts of the vegetable grafting robot is gradually toward refinement and specialization. The seedling feeding device is not only a simple artificial seedling feeding device but also transformed into an automatic seedling feeding device and a root-breaking feeding device; this can reduce the grafting steps and improve the efficiency of grafting. In addition, the emergence of the flexible clamping device and replaceable clamping device can cope with different seedling diameters and avoid the damage to the outer plan skin tissue caused by too large a clamping force. With multiple cutting blades for parallel cutting and precision cutting devices, the speed of the grafted and cutting accuracy have been improved, so the development of refinement and specialization of key components will be the future direction.

Table 5. Comparison of key grafting device designs.

Device	Object	Method	Characteristic
Seedling feeding device	Rootstock	2-PPA parallel mechanism	Automatic feeding seedling
	Rootstock	Intelligent grading library	Intelligent classification
	Rootstock and scion	Screw and slide bar mechanism	Feed seedlings and break roots simultaneously
	Rootstock and scion	Conveyor chain and transfer handle	One person feeding seedlings
Clamping device	Rootstock and scion	Buffer material	Flexible clamping
	Rootstock	Clip piece and spring	Clamping force can be adjusted
	Scion	Y-cylinder and claw	Clip seedlings and break roots simultaneously
	Rootstock	Cylinder and collet	Integral clip body and independent collet
Cutting device	Rootstock and scion	Rotary cutting	Synchronous cutting
	Scion	Lateral slide cut	Cutting plane is neat
	Rootstock and scion	XY adjustment mechanism	Precise adjustment of cutter position
	Rootstock and scion	Multiple cutting blades side by side	Cut more seedlings

4. Applications of Machine Vision in Grafting Technology

Machine vision is a branch of artificial intelligence that is developing rapidly. It is mainly used in various fields by obtaining images, converting them into relevant signals and obtaining information such as the shape and characteristics of the target through a special processing system, and then conducting subsequent operations according to this information. This technology is also used by researchers engaged in the development of grafting robots.

4.1. Application in Feature Information Recognition

The characteristic information, such as the direction of cotyledon expansion, the height and coordinates of the growing points of the rootstock, and the length of the seedling, is of vital importance for judging whether the rootstock and the scion can be matched and grafted. Therefore, the correct recognition of the characteristic information of the seedling is one of the key technologies to realizing the whole process automation of the vegetable grafting robot. The development of machine vision technology provides an effective method for obtaining the characteristic parameters of seedlings. He et al. and Xu et al. [51,52] adopted the method of foliar fitting to restore the shape of the leaf and extract the characteristic information of the leaf surface. He et al. used the ellipse fitting method of the least-squares method to restore and parameterize the shape of the leaf surface of the seedlings. Xu et al. used an improved random ellipse Hough transformation on the boundary of the seedling cotyledon image to fit the contour curve of the cotyledon. They built the elliptic mathematical model of cotyledon contour to obtain the characteristic information of seedling leaf surface. Both automatic detection algorithms could extract characteristic information such as the direction of seedling cotyledon expansion, the position of seedling growth point, and the area of cotyledon leaves. By using the optimized minimum circumscribed circle algorithm on the extracted target contour, Zhou et al. [53] obtained the opening angle of the cotyledons of the rootstock seedlings and calculated the longest section width of the rootstock seedlings based on the vertical method. Zhang et al. [54] developed a comprehensive image processing algorithm, which could extract various characteristic information such as the coordinates of the growth point of the grafted seedlings, the diameter of the long and short axes of the seedling stem section, and the length of the seedlings. Gong and Li [55,56] accomplished cotyledon image processing by analyzing the images projected on the horizontal and different vertical planes of rootstock seedlings. Based on this, Gong extracted the region of the growing points by the image segmentation method and calculated the coordinates of the growing points by the gravity center method. Li used analytic geometry to detect the position of the growing point. Both of them accomplished the identification of the rootstock cotyledon unfolding direction and the determination of the height of the growing point by using the automatic detection algorithm. Liu et al. [57] developed a set of software for seedling identification and geometric parameter measurement, which could measure parameters such as the height, thickness of stems, and the horizontal deflection angle of cotyledon by positioning and identifying images of collected seedlings. All the above methods show good performance in extracting the corresponding feature parameters and improve the grafting speed and success rate of the grafting robot.

4.2. Application in Seedling Grading

Before the grafting process, the quality and survival rate are directly affected by the matching of seedling stem sizes and the recognition of seedling stem curvature, so it is necessary to grade the seedlings before grafting. The traditional method of grading seedling stems usually use the human eye to roughly judge the thickness of the seedlings and make a selection. Considering the artificial limitation, the accuracy of seedling stem grading can't be guaranteed. To improve the grafting survival rate, it is necessary to add a machine vision grading system to the grafting robot. Zhao et al., Ashraf et al., and Wang [58–60] used the statistical method of the accumulation of pixel gray values to process the image and obtained characteristic information such as the curvature of the seedling, and the diameter of the seedling stems from the image by using the classification algorithm, so the identification and matching of rootstocks and scions of different diameters have been accomplished. Therefore, automatic grading of grafted seedlings before grafting can not only improve grade accuracy and reduce labor but also improve the speed and quality of grafting.

4.3. Application in Other Ways

Some attempts at the application of machine vision detection have been made. Kang et al. [61] calculated the amount of bending of seedlings by identifying and processing the images of the collected stems and used servo motors to precisely control the rotation angle of the gripper to achieve the precise junction of the section of rootstock and scion. This can avoid grafting defects caused by stem bending and improve the grafting survival rate. By analyzing the seedling image, Liu et al. [27] accurately identified the position of the grafting point of the rootstock and the scion and the deviation between the hypocotyl tip of the scion and the punctured target point. They then guided the robotic arm to accurately puncture the growing point of the rootstock so that the hypocotyl tip of the scion could be accurately inserted into the hole of the rootstock. Xu et al. [62] analyzed the structure of the pith cavity of the rootstock and morphological characteristics of a machine vision system, built a cutting model, determined the cutting angle and cutting surface parameters, and accomplished the precise cutting and grafting of the rootstock and scion seedlings. Liu et al. [63] developed a gap detection system based on the template matching method. The gap recognition algorithm was used to compare the gap image of grafted seedlings with the generated template image to verify whether the gap between the anvil and spike of grafted seedlings was qualified. Tian et al. [64] determined that the selection of a UXGA monochrome camera and blue backlight without a filter device was the best choice for sorting and inspecting of seedlings.

As shown in Table 6, during the grafting process, the realization of a fully automated grafting operation depends on correctly identifying the operation object. Only by using machine vision technology to identify the state of seedlings the subsequent grafting operation can get prepared. The use of foliar feature information recognition technology can remove the influence of individual differences and uncertainties on seedling grafting, and the classification of seedlings before grafting can solve the problem of matching the diameters of different rootstocks and scions. The gap recognition algorithm is used to identify the combined part of rootstocks and scions and determine whether the gap is qualified. Therefore, the application of machine vision technology is the only way to achieve full automation of grafting robots.

Table 6. Comparison of various applications of machine vision in grafting.

Application	Object	Method	Purpose	Success Rate
Identify the characteristic information of seedlings	Rootstock seedling	Ellipse fitting method	Cotyledon growth direction, location of growth points and leaf area	97.5%
	Rootstock seedling	Hough ellipse fitting	Cotyledon growth direction, location of growth points and leaf area	85%
	Rootstock seedling	Minimum circumscribed circle method	Cotyledon opening Angle	99. 58%
	Rootstock seedling	Integrated algorithm for image processing	Coordinates of growth points diameter of the long and short axes of the seedling stem section, and seedling length	-
Classification of seedlings	Tomato seedlings	Statistical method of Pixel gray value accumulation	Curvature and diameter of seedlings	96%
Seedling inspection	Grafting finished seedlings	Gap recognition algorithm	Check the clearance of the bonding surface	-
Auxiliary grafting	Drill the target point and scion	Machine Vision positioning technology	Positioning before drilling	-

Grafting has three main processes: cutting, joining, and picking [65]. With the help of artificial intelligence technology, the fully automatic grafting robot can accurately cut and locate seedlings according to their size and spatial position, improve the size measurement accuracy and activity space of the cutter, and ensure that the cutting system has super adaptability. The intelligent control method of deep learning and the precise design of the structure can be used to realize the flexible clamping and precise nondestructive connection of scion and rootstocks. In the process of grafting and picking, machine vision technology is used to conduct state identification, classification, and defect detection of the seedlings, which greatly improves the grafting success rate of the grafting robot.

With the rapid development of modern 5G and Internet of Things technologies, timely data explosions are generated in the process of vegetable grafting by means of monitoring, collecting, and identifying based on artificial intelligence means. These data are diversified, diverse, and heterogeneous, which makes it difficult to obtain important data information about grafting techniques. With the help of deep learning artificial intelligence methods of search and solution, knowledge and reasoning, and learning and discovery, in-depth data mining can provide a large number of data references for the accurate monitoring and control of automatic grafting robots, optimization of grafting seedlings, accurate prediction and optimization of process parameters.

In addition, with the continuous development of cloud technology, combined with the big data system of modern grafting technology and seedling breeding technology, it is possible to build a seedling variety information database and database, seedling importance status regulation network database, seedling bio-informatics, and biometric data analysis system based on the cloud platform and remote computing, so as to realize the big data terminal processing requirements of vegetable grafting process, seedling agronomic growth and grafting equipment status. At the same time, by introducing various advanced sensors and wireless sensor networks to collect a large amount of useful information and uploading it to the cloud database in a timely and rapid manner, the real-time responsiveness of the big data is increased. On this basis, through artificial intelligence methods such as data mining and deep learning, the mapping between efficient and clear grafting process parameters and the cloud database is established. The grafting breeding model is built to accurately determine the health status of grafting individuals and groups and the grafting environment, select the optimal grafting process and process parameters, and analyze and early warn the parameters of the grafting process. Finally, the intelligent decision of automatic grafting is realized.

5. Existing Problems and Future Development

5.1. Existing Problems

After analyzing the key technologies and research status of vegetable grafting robots, it can be seen that most of the current research on vegetable grafting robots is still in the testing or prototype stage, and the application shortcomings are also obvious, mainly including the following aspects:

5.1.1. Limited Grafting Rate

With the increasing demand for the number of grafted seedlings, the speed of manual grafting seedlings has been maintained at 600–800 plants/h, which can no longer meet the actual demand [66]. On the one hand, the level of control and manufacturing is constantly improving. For a single plant grafting robot, the grafting rate is maintained at about 1000 plants/h. Compared with manual grafting, there is not much advantage, and seedling companies cannot accept robot substitutions. On the other hand, the grafting period of vegetables is short, and the amount of grafting is large in agronomic production. If the grafting can't be completed on time, the suitable grafting period will be missed, and the cost of seedling raising and management will also increase.

5.1.2. High Manufacturing Cost

The grafting robot has a complex structure and control system. On the one hand, the higher the degree of automation of the grafting robot, the more advanced the required supporting equipment is needed. On the other hand, the high price of the fully automatic grafting robot makes it impossible for small and medium-sized seedling enterprises to afford it [67]. So, the high production cost of grafting robots needs to be solved.

5.1.3. Lack of Auxiliary Equipment for Grafting

Nowadays, grafting technology has gradually matured, and the importance of grafting auxiliary equipment is gradually being displayed, such as the development of unified and precise seeding equipment, the device of matching and grafting intelligent detection system for seedlings, the automatic replanting system for grafted seedlings, and greenhouse logistics and other supporting systems. For the development of grafting technology, all of these should be continuously researched.

5.2. Future Development

Through the research and analysis of the current development of grafting robots, it can be seen that there are many key technologies of grafting robots that have not yet been solved, and there is still a lot of room for improvement. At present, agriculture is in the transition stage from the automation and information age to the intelligent era, and the future vegetable grafting robot should also keep up with the pace of the times and develop towards the following aspects:

5.2.1. Automation and Intelligence of Vegetable Grafting Robot

With the rapid development of industrialized seedlings, automated grafting will also be widely used in the industrialized seedling field. In recent years, with the aging of the population and the gradual increase in labor costs, the manual grafting operation mode can no longer meet the market demand. Automatic grafting is an inevitable trend, such as developing an intelligent human-computer interaction system, building an automatic grafting supporting production system, establishing an intelligent seedling detection and matching system, and so on [68]. All of these can achieve the automation of the entire grafting process. Moreover, with the improvement of the degree of automation of the grafting robot, more modern agronomic technology, and artificial intelligence technology will be combined to make the grafting robot more powerful in the future.

5.2.2. Machine Vision AI Technology Based on Grafting Process and Automatic Diagnosis Technology

At present, the degree of automation of vegetable grafting robots is increasing, and the grafting process is gradually developing towards the direction of refinement. It is necessary for the grafting robot to improve the accuracy of grafting technology and add automatic diagnosis technology. As the largest information source for vegetable grafting robots, machine vision can be widely used in the detection of various seedlings' information during the grafting process, and the success rate can reach more than 90%. However, at present, because the machine vision needs to choose an appropriate hardware structure and software system, such as camera, lens, and the selection of appropriate lighting resources, it will increase the cost of research and development and purchase of grafting robot and has not been widely used. In the future, several operations can be assisted by machine vision, such as the identification and matching of the diameter of seedlings before grafting, the detection of the deviation of the joint surface of the seedlings during grafting, and the detection of the gap between the rootstock and the scion after grafting. All of these will greatly improve the survival rate of grafted seedlings. In addition, combined with some successful methods in the field of artificial intelligence, the automatic grafting robot will become more intelligent by making full use of the big data generated by the grafting process. Therefore, only when the research of robot vision technology is broken through can the precise operation of vegetable grafting robots be realized.

5.2.3. Low-Cost and High-Efficiency Grafting Robot

Nowadays, in the automatic grafting production line of the industrialized seedling factory, the grafting robots are controlled based on single seedlings for automated grafting operations, and their work efficiency is generally maintained at about 1000 plants/h. Compared with manual grafting, there is not much advantage. It is necessary to develop a high-efficiency grafting robot that can feed multiple seedlings at the same time. In addition, the grafting robot needs to complete the execution of multiple actions in the process of the grafting operation. As long as there is a problem in the execution of one action, the entire grafting process will fail. Therefore, the structure of the grafting robot is relatively complicated, which directly leads to the high cost of the existing grafting robot, and the difficulty in control is a "stumbling block" on the road of the grafting robot to the farmers [69]. The optimal solution must be found between cost and efficiency if the grafting robot is to be widely used in seedling enterprises.

6. Conclusions

(1) Combined with some related biological science and agronomy research, researchers in various countries have carried out a lot of research on vegetable grafting robots. In the process of their development from semi-automation to full automation, a large number of useful achievements have been obtained, and the grafting speed and survival rate have been greatly improved. Considering the development of disciplines such as agronomy and mechanical design, the current vegetable grafting robots based on the splice grafting method are more suitable for the development of mechanization and automation, which are the mainstream and development direction of future research.
(2) With the rapid development of mechanical design and control theory, the design direction of the key grafting devices of vegetable grafting robots is gradually moving towards refinement and specialization, such as automatic seedling feeding, flexible clamping, and precision cutting. At the same time, the application of modern intelligent methods such as machine vision technology can extract feature information from seedlings, solve the impact of seedling differences and uncertainties on grafting, and truly realize the full automation of grafting. This is also one of the development directions of key technologies for vegetable grafting robots in the future.
(3) With the continuous development of information technology and the gradual application of cloud computing and big data in the field of agriculture, the construction of intelligent agricultural systems has become the general direction of future development. Through modern sensing technology and Internet of things technology, timely collection of a large number of related data during the grafting process, the use of modern artificial intelligence methods such as data mining, deep learning, and cloud computing technology, timely data analysis and optimization of process parameters can be carried out for accurate grafting operations and intelligent management of facilities. At the same time, with the help of modern artificial intelligence, big data, and cloud computing methods, it is also an important task and challenge to construct the design model of vegetable grafting robots based on agronomy and mechanism.

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