DEVELOPMENT OF A CIRCULAR GRAFTING ROBOTIC SYSTEM FOR WATERMELON SEEDLINGS

Y. C. Chiu, S. Chen, Y. C. Chang

ABSTRACT. The aim of this research was to develop a top plug-in grafting robotic system that is applicable for grafting a scion into a mature rootstock before the scion's cotyledons spread. This would require the scion to be very delicate and greatly different from the rootstock in terms of seedling age. The grafting robotic system for watermelon seedlings consists of a rootstock processing unit and a scion processing unit, with dimensions of 120 cm × 105 cm × 130 cm. Both the rootstock and scion processing unit have a rotating disc, with the disc of the rootstock processing unit being lower than that of the scion processing unit; furthermore, the two discs rotate in opposite directions. A Geneva Wheel intermittent motion mechanism was adopted to drive the discs so that simultaneous and opposite movement was possible. The rootstock processing unit takes charge of removing the leaf bud from the rootstock seedling and drilling a hole for the scion, while the scion processing unit performs the action of cutting the scion seedling to make a sharp angle and finishes the grafting operation by inserting the scion into the hole in the rootstock. The developed grafting robotic system is characterized by the absence of grafting clips. This research employs bottle gourd “Chiang-Li #1” as the rootstock and watermelon “Fu-Bao #2” as the scion to conduct a series of mechanical grafting experiments. The experimental results showed that the grafting robotic system was able to accurately finish all grafting procedures and operations, with an average success rate of 95% and a working capability of 480 seedlings per hour. Demonstrations were held and farmers were highly satisfied with the system's functions and its performance.

Keywords. Automation, Rootstock, Scion, Propagation.

Grafting refers to the process of attaching the plants to be reared, called scions, onto vigorous rootstocks in order to enable the scions to grow, bloom, and fruit well by utilizing the nutrients absorbed by rootstocks. Graft-culture has many advantages, such as resistance to soil-borne disease, increased growth vigor and better biological metabolism, enhanced tolerance to a poor environment, and improved production quality and quantity (Dai, 1998).

In recent years, fruit-bearing vegetable crops, such as watermelons and tomatoes, planted in Japan, South Korea, Taiwan, China, and other Asian and European countries have suffered from wilt disease and root-knot nematodes. This problem is caused by continuous cropping on the same area because, in these countries, land use is very intensive. These problems affect the quantity, quality, and overall survival of the crop. As a result, for melons planted either inside greenhouses or in the field, a trend has developed to graft them onto rootstocks with good disease-resistance and vigor. In this way, the quantity and quality of the crop can be improved and the period of rotational planting can be shortened. Grafting was later introduced in Europe, Africa, the Middle East, and North America. Many countries adopted the technology during the past two decades (Kubota, 2008).

In Japan, the crops that use grafted seedlings include watermelon, cucumber, muskmelon, eggplant, and others. More than 85% of these crops grown in a greenhouse use grafting seedlings. For watermelon, this reaches >95%, both in the greenhouse and in the field (Lee, 1994); furthermore, the proportion continues to rise. In Taiwan, farmers growing crops such as watermelon, bitter melon, tomato, passion fruit, and papaya are gradually adopting grafted seedlings. In terms of seedling requirements by farmers, it seems likely that grafted seedling will continue to become more and more popular. Among the above crops, watermelons are in the majority. Based on the Taiwan Agriculture Statistics Yearbook (2010), the watermelon crop area for the year is about 12,665 ha, and, based on 1500 seedlings/ha, the annual demand for watermelon seedlings is about 19,000,000. Based on this demand, many grafting nurseries have been established to provide melon farmers with grafted seedlings using specialized production. However, grafting is a highly labor intensive operation and demands technically trained workers rather than ordinary laborers. In order to alleviate the lack of skilled workers, it is necessary to develop grafting robots to provide sufficient grafted seedlings to farmers.

The three common rootstocks for watermelon are bottle gourd, pumpkin, and wild-grown watermelon, each of which is appropriate to a different situation. The methods employed in grafting include top plug-in grafting, side plug-in grafting, approach grafting, whip grafting, and terminal cleft grafting (Luo and Chen, 1990). Most of the watermelon seedlings

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produced in Taiwan adopts the top plug-in grafting method. The operation capability by hand is about 215 seedlings/h.

In addition to the high labor needs and rigorous technical standards that are required by a grafting operation, it is not easy to find and train professional skilled grafting workers. Therefore, there has been a worldwide and urgent need to develop labor saving or automatic grafting robots for nurseries. Japan has been actively engaged in the development of grafting techniques because of its widespread use of grafted seedlings. Various types of grafting robots have been developed by the ISEKI Company (ISEKI, 2010); these grafting robots are modified from the ones developed by the Biology Research Organization (Kobayashi and Suzuki, 1996; Kobayashi et al., 1996) and then commercialized. The working capacity of these robots reaches about 900 seedlings per hour with three persons operating them and has a success rate of more than 95%. This type of grafting robot employs clips to fix the grafting junction of rootstock and scion and it is most suitable for rootstocks and scions that are about the same age. However, these grafting robots are expensive and Taiwan’s farmers do not find them to be cost effective.

Nishiura et al. (1995) of Osaka Prefecture University developed a system of grafting robots that adopted the plug-in method where the robot also needs clips to fix the grafting junction of rootstock and scion. This approach can reduce the mismatch between vascular bundles during grafting, and thus is able to accelerate the healing of grafted seedlings and make the seedlings more vigorous. Ashraf et al. (2009) developed a tomato-seedling sorting algorithm for a full automatic grafting robot, with a 97% sorting success rate. In Korea, Hwang et al. (1997) of Sungkyunkwan University developed a grafting robot that used approach grafting. In China, Zou et al. (2009) developed a rotary grafting machine that has a success rate of more than 88%. In Taiwan, Lee et al. (2001) developed an automatic grafting robot for passion melon that is able to graft 114 seedlings per hour, has a grafting success rate of 70%, and a survival rate of 95%. Chen et al. (2009) developed an innovative grafting robot, using soft rubber tubes as the grafting material that enclosures and fixes the grafting junction of rootstock and scion; this works by utilizing the elasticity and expandability of the rubber soft tubes. The latter grafting robot is suitable for fruit-bearing vegetables where the rootstock and scion seedlings have only a small variation in stem diameter, such as Solanaceae, Cucurbitaceae, and teabush plants. This robot has a success rate of 95.5% and can produce 327 seedlings per hour. Other approaches to grafting robots have been described by Kurata (1994) and Hwang et al. (1997).

Based on the increasing need for grafted watermelon seedlings and the fact that successful grafting robots have been developed, it is important realize that these robots target the grafting of vegetables and fruits using rootstocks and scions seedlings that are very similar in age. However, in Taiwan, the scions of the watermelon seedlings are grafted immediately before their cotyledons spreads, so there is a major difference between the age of the rootstock and scions. This practice alleviates the scion of sowing in trays to save nursery cost and to shorten the scion growing time for suitable grafting. In summer, about 12 days after the sowing is the proper time for the rootstocks to be grafted, while in winter it is approximately 18-20 days. In contrast, in summer, scion seedlings are grafted only 4 days after sowing, while in winter this increases to approximately 7 days. Based on these needs, the aim of this research was to develop an automatic grafting robotic system that could be applied to grafting seedlings of watermelon. The approach adopted was top plug-in grafting, which is characterized by the absence of graft clips; in this context, this method is applicable to grafting scions immediately onto mature rootstocks before the cotyledons of the scions spread. Such an approach allows very sensitive scions, which greatly differ in the seedling age from the rootstock, to be grafted onto much older rootstocks.

**MATERIALS AND METHODS**

**DESIGN OF THE GRAFTING ROBOT**

The circular grafting robotic system for watermelon seedlings consists of a rootstock processing unit and a scion processing unit. The rootstock processing unit is in charge of the removal/pinching of the leaf bud from the rootstock and drilling a tiny hole into the center of the rootstock’s stem in order to facilitate the plug-in of the scion. Meanwhile, the scion processing unit cuts off the bottom of the scion, leaving the scion with an oblique cut, and then plugs the beveled hypocotyl into the hole in the rootstock, which completes the grafting operation. The robot is designed to be semi-automatic, and utilizes the manual placing of the rootstock and scion separately into the two positioning grippers. After the robot automatically grafts the scion into the rootstock, there is manual removal of the grafted seedling. The operational flow is shown in figure 2.

Both the rootstock and scion processing units have a rotating disc drive by a single-phase 220-V, 60-W motor; the disc of the former is lower than the disc of the latter and the two discs rotate in opposite directions. The center distance between the two discs is 420 mm. The rotating discs operate using intermittent movements that are driven by a Geneva Wheel intermittent motion mechanism; this facilitates the leaf bud removal, drilling, scion cutting and grafting operations. The Geneva Wheel intermittent motion mechanism consists of 12 partitions, which means that the driven shaft only rotates 30° when the driving shaft has rotated one full circle. A total of 12 seedling grippers can be installed on each of the two rootstock and scion processing unit discs and in this study we used a system with four grippers. After the disc rotates one circle, the grafting of four seedlings is completed. The rootstock and scion processing units must be positioned accurately, and time adjustment is

![Figure 1. Schematic diagram of top plug-in grafting.](image-url)
also very important, otherwise the scion cannot be accurately inserted into the rootstock. Therefore, it is necessary to employ a timing belt to adjust the gearing and timing. Figure 3 shows a prototype of the grafting robot.

**Rootstock Processing Unit**

The rootstock processing unit is composed of three parts: grip-conveying, leaf bud removal, and drilling (fig. 2). The grip-conveying part is made up of the rootstock grippers, a rootstock tray, and a turnplate (fig. 4). The rootstock grippers are fixed on the turnplate, and each gripper is separated from the next nearest ones by 30°. In addition, there is a round hole, with a diameter of 4 mm, in the center of each gripper to allow placing of the rootstock seedling. The grippers are automatically opened and closed through control by the cam. This works such that when the gripper moves into the seedling supply position, the cam rises to drive the roof, compresses the spring, and this opens the gripper. At this point, the rootstock is horizontally placed into the gripper by a worker’s hand. There is a tray below the gripper, which supports the rootstock and it is supported in the horizontal plane by a support bar. When the gripper moves forward along with the disc, the cam falls, the roof is restored by the spring and the rootstock is gripped by the gripper. The rootstock will continue to be upright as it rotates to be in front of the leaf bud removal system. At the same time, the tray also remains upright due to the lack of the support by the support bar. The cotyledons of the rootstock are required to be at an angle of 90° with respect to the gripper, and the rootstock is prevented from dropping by the top of the gripper, which supports the rootstock.

The leaf bud removal unit consists of a push-lever and a clamp for leaf bud removing (fig. 5). They are fixed on a seat, and move up and down when the pneumatic cylinder drives the fixing seat. The clamp performs the operations of picking and clamping through another pneumatic cylinder. When the rootstock seedling is conveyed to the leaf bud removal area by the turnplate, the fixing seat shifts downward, the push-lever pushes down the cotyledons of the rootstock, and the clamp then removes the leaf bud of the rootstock. The drilling unit subsequently drills a hole in the rootstock using a drill powered by a high-speed motor (11,500 rpm). The high-speed motor moves up and down to control the drilling depth via the lift cylinder of the drilling set.
Scion Processing Unit

The scion processing unit consists of a grip-conveying unit and a cutting unit. The grip-conveying unit includes a turnplate and grippers for the scion seedlings (fig. 6), and the drive shaft of the turnplate, which functions as a cam. The roof moves along the camshaft to control the opening and closing of scion grippers. The roller of the gripper moves along the outskirts of the cam-plate. There is a drop site, with a height difference, at the joining of the rootstock and scion turnplates. After the cutting, the scion seedling is inserted into the hole in the rootstock by utilizing the height difference. The gripper for scion seedlings consists of a bearing bar and a clamping bar, the former having a semi-circular orifice with a diameter of 2 mm for input of the scion seedlings (fig. 6). The cutting part consists of a cutting blade, which creates an oblique cut at about 90° to remove the bottom of the scion via the driving cylinder of the knife bed and the lift cylinder of the cutting blade; this results in a shorter hypocotyledonary axis. The anvil pad of the cutting part is made of a soft rubber material, which allows easy replacement of the part when it wears. At the same time, this type of pad material is able to protect the cutting blade and avoids direct contact between the blade and metal. If such protection were not provided by the system, the grafting success rate and the grafted seedling survival rate would be significantly reduced by uneven cutting. Figure 7 presents the structure of the cutting unit that acts on the scion seedling.

After cutting, the turnplate moves the scion above the rootstock, and then the roller moves to the drop site on the cam plate; the roller and the gripper rapidly fall because of gravity and the spring force of the leading bar, which inserts the scion into the hole in the rootstock; At the same time, through the action of the cam, the roof quickly withdraws and releases the scion seedling, and the grafting process is finished.

EXPERIMENTS INVESTIGATING HOW TO IMPROVE THE STRENGTH AND ERECTNESS OF SCIONS

Farmers in Taiwan cultivate watermelon scion seedlings by sowing the seeds in fluvial sand soils, and the cultivation area is covered with a black shading net. Between 4 and 7 days after sowing, the scions are uprooted and collected; they are then grafted after washing in water. These scion seedlings are slender and delicate like bean sprouts (fig. 8); this means that during the mechanical cutting operation the seedlings are always asymmetrical and curved, which makes insertion into the hole in the rootstock difficult. To overcome this problem, a series of experiments was carried out to improve the strength and erectness of scions by adjusting the lighting. During the germination period of scion seeds, we examined the changes in strength and erectness of scions under various lighting regimes. The aim was to produce scions with a short and strong hypocotyledonary axis and with better erectness that would improve the success rate for mechanical grafting.
Initially the watermelon seeds were sown in a transparent capped plastic case that was 14.5 cm × 10.7 cm × 7.5 cm in size. The case consisted of, from top to bottom, two layers of non-woven plastic film and a layer of black nylon cloth, a growing bed for the seeds and a cloth bed that keeps the seeds moist without any additional growing medium. In this way, the water needed for the germination is provided. After sowing, the case containing the cultivated seedlings was placed in a plant growth chamber with day/night temperatures of 30/28°C. The whole germination experimental time was 6 days and was divided into seven treatments, namely lighting periods of 6 days (lighting), 5 days (lighting from the second day after sowing), 4 days (lighting from the third day), 3 days (lighting from the fourth day), 2 days (lighting from the fifth day), 1 day (lighting on the last day) and the total period without lighting. In each experimental treatment, 30 seeds were sown, and each treatment was repeated for three times. At 6 days after sowing, the seedlings were observed and factors such as germination rate, the average length of the hypocotyledonary axis, and the average stem diameter were measured.

As shown in table 1, the germination rate was found to be above 90% if the lighting time during germination exceeded 3 days; and the longer the lighting time, the higher the germination rate. Conversely, the germination rate drops significantly if the lighting time was less than 3 days. In terms of hypocotyledonary axis length, the shorter the lighting time, the longer is the hypocotyledonary axis, which indicates rapid growth of the scion seedlings. In terms of stem diameter, the influence of the lighting time was insignificant, but a trend towards a greater diameter was present if the lighting regime was 3 or 4 days. Figure 9 shows the scion seedlings after this lighting treatment. Compared with figure 8, it was found that the above approach was able to produce shorter scions with better erectness that were more suitable for mechanical grafting.

**Preparation of Rootstocks and Scions**

This experiment employed bottle gourd “Chiang-Li #1” as the rootstock and watermelon “Fu-Bao #2” as the scion. The seeds for the experiment were purchased from the Known-You Seed Co., Ltd. (Kaoshiung, Taiwan). Before sowing, the seeds of the bottle gourd are soaked in clean water at 30°C for 8 h, and then, after full water-absorption, they were sown into a tray with 60 compartments that had been filled with growth medium (3# King-root for planting, to which was added 3g Osmocote with N: P: K = 14: 14: 14 for each liter of medium). Next, they were placed in a simple plastic greenhouse to sprout. The watermelon seeds for the scion were sown when the cotyledons of the bottle gourd had spread, just before the leaves emerged. Based on the weather, during the higher temperatures of summer, the watermelon seeds for the scion should be sown 10 days after the bottle gourds are sown, while during the lower temperature of winter, this should be 16 days later. The watermelon seeds were also soaked into clean water at 30°C for 8 h, and then, after full water-absorption, they were sown directly in the plastic case system described above. Then the case was placed in the growing chamber with day/night temperatures of 30/28°C and provided with a light supply. About 6 days later, the hypocotyledonary axis of watermelon seedlings reaches 3 to 5 cm in length, and the seedlings can be prepared for grafting before the cotyledon spreads.

**Healing Conditions after Grafting**

After grafting, the grafted watermelon seedlings were moved into an acclimatization chamber (Chiu et al., 1999). (temperature: 25°C~29°C; relative humidity 90~95%; time with artificial lights on: 8:00~20:00; time when ventilation windows are open: 18:00~06:00, once for 5 min every hour). The grafted seedlings in the acclimatization chamber were watered every day from above using a bottle. The chamber was turned on for 1 h before the grafted seedlings were moved in, which enabled the environment to meet the preset conditions. The survival rate was recorded 7 days after grafting.
Experimental Factors and Conditions

Each time before the experiment, the cutting blade for the scions was replaced with a new blade. The new blade was sterilized with alcohol to limit contamination and improve the survival rate of scion seedlings. As part of the experiment design a number of factors needed investigation. First, it was necessary to deal with the problem of medium fallout during mechanical grafting. Secondly, experiments were carried out to evaluate whether the rootstock and scion were tightly united by top plug-in grafting method. Finally, an investigation into whether the pressing of cotyledons during the mechanical leaf bud removal influenced the survival rate of the grafted seedlings was carried out. Under each experimental condition, 20 seedlings were grafted and the mechanical grafting success rate and grafted seedling survival rate were observed. The experiments were repeated twice. The experimental specifications were as follows:

Group A (machine control group): complete machine grafting.

Group B (manual leaf bud removal, mechanical grafting): the grafting operations were carried out by the machine, but the machine was not used leaf bud removal and pushing down the cotyledons. Specifically, the growing point was manually removed to compare this with the severity of damage to the cotyledons caused by the mechanical pushing down.

Group C (machine + clips): total use of the machine to do the graft, but grafting clips were added after the grafting.

Group D (manual removal of leaf bud + clips): repeat the operations in Group B, but grafting clips were used after the machine finished the grafting operation.

Group E (manual support to the medium): the machine was used to graft, but the soil medium was supported with hands as the rootstocks moves from horizontal state to upright state to avoid fallout of the soil medium.

Group F (manual control group): grafting was carried out completely by manual operation.

Using the above groups, the influence of the following factors on the survival rate could be compared:

The pushing down of cotyledons before leaf bud removal and its influence on survival rates was observed by comparing Group A and B.

The effect of grafting tightness on survival rate was examined by comparing Group A and C and Group B and D.

The effect of fallout of soil medium on survival rate was examined by comparing Group A and E.

Group F was used to compare all of the other groups with a purely manual grafting approach.

RESULTS AND DISCUSSION

A prototype of the circular grafting robotic system for melon seedlings, with dimensions of 120 cm × 105 cm × 130 cm, is shown in figure 10. This system is characterized by the fact that the top plug-in grafting does not require the use of a grafting clip. The operation of the grafting robot requires two operators who are responsible for supplying the rootstock and scion seedlings, and also for placing the grafted seedling back into the tray after the grafting is finished. Figure 11 shows a grafted seedling produced by the mechanical grafting system.

Figure 10. Prototype of the circular grafting robotic system for watermelon seedlings.

Figure 11. Finished grafted seedling.

RESULT OF GRAFTING SUCCESS RATE

Functional experiments in the initial phase showed that the grafting robot was able to accurately perform each procedure and action needed for the grafting. However, it was found during these experiments that the quality of rootstock greatly affected the success rate of the grafting, as well as the subsequent survival rate of the grafted seedlings. If the diameter of the rootstock is too small, the stem breaks easily when it is being drilled, which causes bacterial infection and grafted seedlings loss. Hence thick and strong rootstocks suitable for the mechanical operation were necessary. Two experiments were conducted on 2 February 2002 and 4 April 2002, respectively. Table 2 shows the hypocotyledonary axes lengths and the stem diameters of 20 rootstocks and 20 scions randomly chosen from the second experiment. The success rate for each experiment trial is shown in the table 3. The turnplate of the grafting robot turns at the rate of 1 rpm and has an operation capability of 480 seedlings/h when the machine is fitted with 12 gripper arms. The experiment was set to graft the next seedling once it finishes grafting the current seedling. The grafting operations in groups A, C, E were all performed by machine. The average success rate of
The watermelon scion seedlings used in traditional manual grafting are as slender and delicate as bean sprouts, which created difficulties in mechanical grafting. This removal of the growing point (leaf bud removal) and skipping the mechanism of pushing down the cotyledons was 89%. From this, it can be concluded that the pressing of the cotyledons by the machine did not significantly affect the survival rate. A comparison of Groups A and C showed that the use of grafting clips to increase the tightness between the rootstock and scion after machine grafting had no significant effect on survival rate. The average was 88.9% for the group using clips, compared to 89.5% for the machine control group, only a small difference. Based on a comparison between Groups B and D, it was found that manual removal of the leaf bud and the use of grafting clips to increase tightness resulted in the survival rate improving from 90% to 100%. When Group A and E were compared, it became obvious that fallout of the soil medium due to turning the grafting robot vertically did affect the survival rate of grafted seedlings. Group E, where the medium soil was supported by hand to avoid fallout as the turnplate moves to vertical, allowed the growth of a more complete root system; the result was a survival rate of 100% in Group E, which is higher than the 89.5% in Group A. Thus fallout did affect to some extent the overall survival rate.

CONCLUSIONS

The aim of this research was to develop a top plug-in grafting robot that could graft a scion onto a mature rootstock before the scion’s cotyledons had spread. This robot needed to be able to handle a scion that is very delicate and greatly different from the rootstock in seedling age. Using watermelon grafted seedlings as the model system, the grafting robot was able to conduct the mechanical process of top plug-in grafting, which used watermelon seedlings as the scion, and bottle gourd, pumpkin and wild-growing watermelon seedlings as the rootstock. This top plug-in grafting did not require the use of grafting clips, which has become a characteristic of machine grafting. Taking watermelon seedlings as an example, the success rate can be as high as 95% and the operation capability of the machine is 480 seedlings/h. The operation of the grafting robot requires two operators who are responsible for supplying the rootstock and scion seedlings, and also for placing the grafted seedling back into the tray after the grafting is finished. Demonstrations were held and farmers were highly satisfied with the system’s functions and its performance. However, the operation capacity is only slightly higher than the manual grafting. Therefore, further improvement on the machine capacity is necessary. At present in Taiwan, the lack of farm labor may increase the market interest in this type of machine.

The watermelon scion seedlings used in traditional manual grafting are as slender and delicate as bean sprouts, which created difficulties in mechanical grafting. This
research used a modified lighting method to improve the strength and erectness of scion seedlings. The experimental results show that when the lighting time exceeds three days during germination, the germination rate reaches >90%. Moreover, the modified lighting was able to produce shorter scions that have better erectness which makes mechanical grafting easier. In addition, it was found experimentally that the root system of the bottle gourd rootstock might be damaged during the mechanical grafting if the root system has not formed a proper root cluster. If damage occurs, then the whole plant may ulcerate or the stem base might rot. Changes to the mechanical system or to the process carried out by the human operator should be able to alleviate this. Finally, bacterial infection can be a problem and therefore the introduction of a sterilizing step for both the drill unit and the cutting blade would be useful as a way of reducing the possibility of bacterial infection.

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