Development of a Vision Guided Robot for Grafting Watermelon Based on Hole Insertion Method

Kai Liu¹, Kai Jiang²* and Yanqiu Mu³

¹Guangdong Mechanical and Electrical Polytechnic, Guangzhou 510515, China
²Beijing Research Center of Intelligent Equipment for Agriculture, Beijing 100097, China
³College of Science, Northeast Agricultural University, Harbin 150030, China

Abstract. The grafting success rate of existing grafting robots will be significantly affected by individual differences in seedling’s shape. To circumvent this problem, a vision guided robot consisting of a Denso manipulator, a scion cutting unit, a rootstock holding unit, a Cognex machine vision system, a control system, and an end effector was developed. The robot autonomously performed its grafting task using a machine vision to locate the punching target point and the tip of scion hypocotyl, and then control system regulated the manipulator to punch a hole on the rootstock stem and accurately insert the watermelon scion into the hole. The function experiment showed that the punching angle of pin used by robot was 60° and the maximum inserting speed should not exceed 25 mm/s. Grafting experiment results showed that For the seedlings with individual differences in seedling’s shape, the success rate of present grafting robot (95.6%) is higher than that (83%) of a early grafting robot (2JC-600B). It is obvious that vision guidance reduce the negative effect of individual differences in seedling’s shape on grafting success rate.

1. Introduction

Grafting, using resistant rootstocks, can not only minimize the problems associated with successive cropping and stress tolerance (Fallik et al., 2013; Hartmann et al., 2010), in addition, it has many advantages, such as better biological metabolism, reduce reliance on chemical and fertilizer inputs and improved production quality and quantity (Camacho-Ferre et al., 2013; Fallik et al., 2014). In recent years, grafting has been widely adapted on a commercial scale in Japan, Korea, China, and other European countries (Hassell et al., 2008; Kim et al., 2015; Sakata et al., 2007).

In China, With the rapid development of the continuous adjustment of planting structures, cucurbit vegetables cultivation areas, such as watermelon, accounting for 58.1% of the total fruit cultivation area in the world in 2009 (Lee et al., 2010), and many grafting nurseries have been established to provide watermelon farmers with grafted seedlings. However, grafting still depend mainly on manual labor, in addition to the rigorous technical standards required by a grafting operation, it is not easy to find and train professional skilled grafting workers (Chiacchio et al., 2018). Therefore, there has been an urgent need to develop automatic grafting robots for nurseries.

The methods used by grafting robots vary with variety of crops being grafted. For watermelons, hole insertion grafting is most popularly used in the world (Lee et al., 2010). As shown in Figure 1, the process of hole insertion method involves punching a cone shaped hole in the rootstock stem, cutting the scion at a slant angle to the longitudinal direction, and inserting the scion into the hole in the rootstock stem. The author thinks that it can be used as a new method of mechanical grafting, which
has the following advantages (1) it does not need fixings such as grafting clip, and it is easy to operate, simple process, and realize mechanical operation; (2) it is not easy to insert cracked rootstock, and the scion is relatively firm; (3) it is convenient to remove fixings such as grafting clip after grafting healing administration; In Taiwan, Chiu et al developed a grafting robotic system that adopted the hole insertion method (Chiu et al., 2010). In China, Gu et al have been researching on the grafting robot using hole insertion method for a decade. The grafting robot (2JC-600B) was commercialized in 2010 (Chu et al., 2011). However, for lack of position feedback, the grafting success rate of the robots discussed above will be significantly affected by individual differences of seedling’s shape. In order to solve the problem and achieve high grafting success rate, a vision guided robot was developed to recognize and locate rootstock and scion, then accurately punch a hole and insert the watermelon scion into the hole.

![Figure 1. Hole insertion method](image)

(1). Scion; (2). Scion cutting; (3). Rootstock; (4). Punch a hole in the rootstock; (5). Grafting

2. Materials and Methods

2.1. Construction of the Robot

As shown in Figure 2, The robot included a Denso manipulator with six degrees of freedom (6-DOF), a scion cutting unit, a rootstock holding unit, a Cognex machine vision system, a control system, and an end effector. The end effector contains two parts: a punching unit and a scion holding unit.

Machine vision system was used to capture the image of seedlings and guide the manipulator. The system included a Cognex In-Sight micro camera, a cold light illuminator and a recognition software package. The camera was triggered by robot controller. Cold light illuminator was used to enhance the contrast of the features in the image. With a space limits, a fiber-optic cable was used to transmit the light from cold light illuminator.

![Figure 2. Layout of the vision guide robot](image)

1. Six-degrees-of freedom manipulator 2. Scion cutting unit 3. Cold light illuminator 4. Rootstock holding unit 5. Digital greyscale camera 6. End effector 7. Scion holding unit 8. Rootstock punching unit
2.2. Operational Flow of Grafting

A task sequence of a single grafting operation was as follows (Figure 3):

1. At first, excised the growth tip of rootstock and fixed the rootstock on the rootstock holding unit by manual.

2. Meantime, the scion was feed into the scion holding unit which was placed over the scion cutting unit. After the upper part of scion cotyledons was held by scion holding unit, the under part of scion cotyledons was cut by cutting blade of scion cutting unit at the angle of 30.

3. Machine vision system captured the image of rootstock and located the punching target point where should be punch a hole, and then the deviation between pin and punching target point (Figure 4(a)) was obtained and the control system modified the position of manipulator. At last the pin was drived by manipulator to punch a hole in the rootstock stem at an oblique angle.

4. The end effector was rotated about the Z’-axis to place the scion over the rootstock.

5. Machine vision system capture the image of scion again and located the tip of scion hypocotyl. The deviation between the tip of scion hypocotyl and punching target point (Figure 4(b)) was obtained, and the control system guided the manipulator to insert the scion into the hole in the rootstock stem.

6. The five steps above were repeated after all parts returned to the initial position.

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**Figure 3.** Task sequence of a single grafting operation
2.3. Vision Guidance

The original image captured by camera was shown in Figure 5. Due to the shape of seedling (especially rootstock) is complicated, for machine vision system, the main factor that influence recognizing effect was the image processing method.

![Figure 5. The original image](image)

Based on experiences and knowledge attained in In-Sight Explorer software, several vision processing tools were applied to locate rootstock and scion. The main tools include “Image” tool, “Region” tool, “Pattern Match” tool and “FindMultiline” tool. In the preprocessing stage, the “Image” tool was applied to enhance desirable features while removing or diminishing undesirable features, and then the “Region” tool was used to define the recognize region by specifying the position, size, and rotation, the advantage of “Region” tool is that it can reduce interference of other region and improve the speed of image processing. Finally, the coordinate was converted to real-world coordinate by the “calibrate” tool, and the new coordinate information was transmit to robot controller.

The tools used to locate seedling vary with the different object, the “Pattern Match” tool is used for rootstock because it was specifically designed for object which had relatively similar outline. The location process consists of two phases: training and finding. In the training phase, a region containing an example of the rootstock to be located is manually identified and extracted to create a trained pattern. In the finding phase, the tool will find out other rootstocks which have the same structure as the trained pattern. Based on this tool, two critical points are obtained, to avoid the surface damage of cotyledon in the grafting operation, the middle of the region between two critical points is defined as the punching target points. An example image of rootstock is shown in Figure 6(a).

It is relatively easy to locate the scion by the “FindMultiline” tool because the main target is the tip of the scion hypocotyl whose structure is simple. At first specifies the acceptable black-to-white edge contrast score, and the model detect the recognize region in the image where there is an abrupt change between light and dark (or vice versa) pixels. Once the edge has been defined, the “FindMultiline” tool will create two lines on both sides of the stem, and the point of intersection of two lines is the tip of scion hypocotyl. The example image of scion is shown in Figure 6(b).
2.4. Functional Experiment
The functions of the individual components of a robot influence the total system performance, so two experiments were conducted to determine the punching angle of pin and the inserting speed of scion.

2.4.1. Punching angle of pin evaluation experiment
In punching process, the pin should not punch a hole vertically on the rootstock, otherwise the cavum of rootstock will be damage by the pin and the hypocotyl of scion will gradually enter the cavum with plant growing and then influence the effect of grafting. Therefore, 200 bottle gourd and 200 pumpkin rootstocks were ready for used to figure out the critical angle (see Fig (4a)) which should be calculated as follows:

$$\alpha = \arccos \frac{B}{2A}$$

Where: $\alpha$ is the punching angle, $A$ is the average distance between the vertex of the cavum and one of critical points, $B$ is the average distance between two critical points.

2.4.2. Inserting speed of scion evaluation experiment
The experiment was conducted to study the effect on inserting success rate, and 700 scions and 700 rootstocks were ready for this experiment. The parameters were: three deviation between the tip of scion hypocotyl and punching target point (0, 0.5, and 1mm); and seven air-cannon pressures (0.10, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40 MPa) representing seven scion inserting speeds. The effect of the deviation and the air-cannon pressures (inserting speeds) were studied. During the experiments, inserting process was analyzed by means of high speed photography.

2.5. The Grafting Experiment
In order to determine the effect of vision guidance on grafting success rate, an experiment has been carried out to compare the performance of the early grafting robot (2JC-600B) developed the two grafting robots are shown in Figure 7. Experiment was divided into group A (2JC-600B grafting robot) and group B (present grafting robot). The parameters were: five deviation between the tip of scion hypocotyl and punching target point (0, 0.5, 1, 1.5, and 2mm). The inserting speed and punching angle choose the data obtained from section 2.4 and 1000 scions and rootstocks were ready for used.
3. Results and Discussion

3.1. Functional Experiment

3.1.1. Punching angle of pin evaluation experiment
There are many differences in geometrical dimension between pumpkin and bottle gourd. The critical angle of pin for different rootstock was obtained respectively by calculation. The angle of pumpkin is 65.317°, which is lower than that (68.364°) of bottle gourd. In order to suitable for all varieties, the punching angle used by robots should not over 65.317°. Moreover, to decrease the influenced of cotyledon and ensure the flexibility of designing, in the end, the punching angle of pin used by robots is 60°.

3.1.2. Inserting speed of scion evaluation experiment
The results from inserting speed of scion evaluation experiment are given in Figure 8. For a given deviation, there is no significant change for grafting success rate when the speed is relatively low. However, it is obvious that the success rate dropped rapidly when the grafting speed is beyond a safe speed of 25mm/s. Videos of high speed photography indicate that the reasons for the insert failure is that an excessively high speed will causing scion damage and diminishes the scion’s capability to slip into the hole in the rootstock, and as the deviation increased, the number of scion slip into the hole decreased. Therefore, the maximum inserting speed should not exceed 25 mm/s.

Figure 8. The grafting success rate with inserting speed for various deviation between the tip of scion hypocotyl and punching target point

3.2. The Grafting Experiment
In the course of grafting experiments, for a given inserting speed and deviation between the tip of scion hypocotyl and punching target point, the grafting success rate is recorded. The results are shown in Figure 9.
There are two main reasons why the scion cannot be inserted into the hole of rootstock. One reason, the most important one, was due to the individual differences of scion or rootstock. Another reason was due to the robot itself such as recognize accuracy rate, mechanism precision, and scion cutting quality. Figure 9 show that the effect of individual differences was greater than that of robot itself in group A, but in group B, due to adopt vision guidance, the influence of individual differences is not obvious.

Experiment results also showed that when using the seedlings which have individual differences, the average grafting success rate of Group A and Group B was 83% and 95.6% respectively. Besides, at the same deviation, grafting success rate in Group B was also higher than that in Group A. The result indicated that vision guidance reduce the negative effect of individual differences on grafting success rate.

4. Conclusion
To reduce the negative effect of individual differences in seedling’s shape on grafting success rate of exiting grafting robots and improve accuracy of grafting watermelon onto the rootstock, This study developed a vision guide robot which using a machine vision to locate the growth tip of rootstock and the tip of scion hypocotyl, and then control system regulated the manipulator to punch a hole in the rootstock and graft the watermelon scion onto the rootstock accurately.

The punching angle of pin used by robots is 60° which was obtained by measuring and analyzing all dimensions associated with rootstock, and an inserting speed of scion evaluation experiment demonstrated that the maximum inserting speed should not exceed 25 mm/s, because too high speed could diminish the scion’s capability to slip into the hole in the rootstock. Experiment result showed that for the seedling with individual differences, the average success rate of present grafting robot is 95.6 %, which is higher than that (83.0 %) of 2JC-600B grafting robot. It is obvious that vision guidance has overcome the influence of individual differences to grafting success rate. Experiment results showed that the developed robot could be applied for high grafting success rate.

5. References
[1] Camacho-Ferre and F. El injerto en tomate como alternativa al bromuro de metilo. Experiencias con esta técnica en San Quintín. B.C.-México. II Agro Simp. Int. Téc. Empres. Prod. y Tendencias 2013, 1-3.
[2] Chiacchio F, Petropoulos G and Pichler D. The Impact of Industrial Robots on EU Employment and Wages: A Local Labour Market Approach; Bruegel: Brussel, Belgium, 2018; pp. 1-18.
[3] Chiu Y C, S. Chen and Y. C. Chang. 2010. Development of a circular grafting robotic system for watermelon seedlings. Applied Engineering in Agriculture 26 (6):1077-1084.
[4] Chu Qi, Jiang Kai, Liu Kai and Gu Song. 2011. Experimental Study on 2JC-600 Automatic Grafting Machine. [J].Chinese Agric. Mechanization. 33(1): 183-185.
[5] Fallik E and Ilic Z. Grafted vegetables-The influence of rootstock and scion on postharvest quality. Folia Hortic. 2014, 26, 79-90.

[6] Fallik E, Alkalai-Tuvia S, Chalupowicz D, Zutahy Y, Zaaroor M, Benichis M and Gamlil A. Effect of rootstock and soil disinfestation of quality of grafted watermelon fruit (Citrullus lanatus): A two-year study. Israel J. Plant Sci. 2016, 63, 38-44.

[7] Hassell R L, Memmott F, Liere D G. Grafting methods for watermelon production. HortScience 2008, 43, 1677-1679.

[8] Hartmann H, Kester D E, Davies F T, Geneve R L. Principles of grafting and budding. In Plant Propagation: Principles and Practices, 8th ed.; Prentice Hall: Upper Saddle River, NJ, USA, 2010; Chapter 11.

[9] Jung-Myung Lee, C. Kubota, S J Tsao, Z Bie, P Hoyos Echevarria, L Morra and M. Oda. Current status of vegetable grafting: Diffusion, grafting techniques, automation, Scientia Horticulturae 127 (2010) 93-105

[10] Kim H M, Hwang, S J. Comparison of Pepper Grafting Efficiency by Grafting Robot. Prot. Hortic. Plant Fact.2015, 24, 57-62.

[11] Lee J.M, Kubota C , Tsao S J , Bie Z , Hoyos Echevarria P , Morra L and Oda M. Current status of vegetable grafting: Diffusion, grafting techniques, automation. Scientia Horticulturae 127 (2010) 93-105.

[12] Sakata Y, Ohara T, Sugiyama M, 2007. The history and present state of the grafting of cucurbitaceous vegetables in Japan. Acta Hortic. 731, 159-170.