Original Research Paper

Research and Development for the Hurdle Avoidance During Transplanting Manipulation Based on Kinect Vision Processing

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Abstract: To avoid damage to plants during the transplanting process, a transplanting method based on the combination of the Kinect machine visual system and the low-damage transplanting end effector was proposed to reduce the damage to the stems and leaves from transplanting end effectors during the transplanting process. The inclined manipulator was designed can avoid the characteristics of the seedling itself during the transplanting process to avoid obstacles. Under the experimental condition, the oblique transplanting manipulator assisted by the Kinect vision processing system achieved 4.70% leaf damage, 16.70% stem bending, 83.45% substrate integrity, and the transplanting quality parameters were 87.36%. The completion time of a single transplant was 8.32±0.4 s, the results proved that the low-damage transplanting manipulator based on the machine vision system can effectively reduce the damage rate of the stems and leaves. This obstacle avoidance transplant method can be extended to seedlings planted in 50 plugs. Research and development for hurdle avoidance during transplanting manipulation based on Kinect vision processing can provide theoretical support for future obstacle avoidance transplantation.

Keywords: Kincet Vision Processing, Inclined Transplanting Manipulator, Path Planning, Obstacle Avoidance

Introduction

In facility horticulture, transplanting equipment plays a decisive role in the mechanized production line. The roots of seedlings are easily loosened in the existing transplanting manual operation and the leaves are easily damaged by collision during the transplanting process. Ensuring the integrity of the seedlings during the transplanting process is of great significance for improving the yield of crops in the later stage. Compared with developed countries in the world, there is a large gap between facility agricultural equipment and equipment integration in China. Internationally, the Netherlands, the United States, and other European and American countries already have mature technology in horticulture. For example, Visser Horti Systems, TTA Company, and Flier Systems of the Netherlands are very advanced in the production of equipment in the direction of horticultural transplanting. At present, scientific research units of

Chinese universities and colleges and related technology development companies have also performed technical research and product development for modern horticultural production equipment systems. Zhejiang University, South China Agricultural University, and China Agricultural University have performed much research on fruit, vegetable, and flower transplanting equipment. In addition to these universities, the National Agricultural Intelligent Equipment Engineering Technology Research Center, Guangdong Institute of Modern Agriculture, etc., have performed research and development on fruit, vegetable, and flower transplanting robots. However, these research institutions have done less research on seedling obstacle avoidance transplantation, mainly focusing on the structure of the transplanting manipulator and seldom conducting research on avoidance transplantation based on machine vision. These studies are mainly used to avoid transplanting by modifying the size of the seedling picking manipulator or changing the path, but it is difficult to realize the real-time

change of the path according to the specific size of the transplanted object (Beridze *et al.*, 2020). By combining structure optimization with machine vision, the single seedling transplanting path can be planned by processing the seedling images in real-time, it is more conducive to realizing the obstacle avoidance transplant of seedlings.

This study developed a low-loss multi-hand transplanting mechanical claw. By studying the physical characteristics data of seedlings, the oblique transplanting manipulator is designed and the obstacle avoidance principle of the Kincet visual processing system is studied. We determine the main obstacle avoidance plan, and design experiments to determine the parameters of the manipulator transplanting operation. Afterward, experiments are designed to obtain suitable seedling transplanting parameters and provide a theoretical parameter basis for the final design of obstacle-avoidable transplanting machinery and equipment.

The research is mainly divided into the following parts:

(1) The mechanical properties of seedlings were studied and a test platform for seedling transplanting was designed
(2) The method of seedling edge positioning based on Kinect was studied and the structure of the seedling picking manipulator was designed
(3) An experiment was designed to obtain the optimal structural parameters of the seedling transplanting manipulator and a performance experiment was carried out

The research process is shown as Fig. 1.

Materials and Methods

Experiment Materials

The experiment subject is Bo Lai No.3 pepper seedlings, which are approximately nourished for four weeks and reach the 4-leaf stage to satisfy the transplanting requirement. The substrate ratio used for cultivation is peat: Coconut bran: Perlite = 3:1:1. The substrate tray for the cultivated seedlings is a 21 (3*7) PVC seedling tray. The total measurement of the plug tray is as follows: The upper side of the single hole is 62 mm, the lower size is 30 mm and the total height is 65 mm. According to reference (Qin *et al.*, 2017), the seedling cultivation environment parameters in this experiment are mainly a cultivation temperature of 22° and a substrate humidity of 81%. All experimental cultivation parameters are based on these parameters (Xue *et al.*, 2022; Jin *et al.*, 2020; 2022; Virk *et al.*, 2021).

Through the measurement of 42 pepper seedlings, the height of the stems and leaves of pepper seedlings of the appropriate age was 70.38~108.26 mm. The length of the underground stem and root is 28.56~47.38 mm and the root extension diameter are 15.42~19.86 mm, which is shown in Fig. 2.

Design Scheme of the Manipulator Test Platform

To design a transplanting hand that can avoid obstacles during the transplanting process and reduce damage to the seedlings, a four-claw inclined transplanting manipulator based on a six-degree-of-freedom industrial manipulator is designed, which is shown in Fig. 3. The manipulator in this experiment is the WY760A manipulator, the power drive system consists of six sets of servo motors and relies on an industrial computer to drive the motion of the manipulator. The cylinder and air compressor provide working power for the end effector to complete the action of picking seedlings. The seedling transplanting process test platform is programmed with an industrial manipulator. During the transplanting process, the working inclination angle of the seedling transplanting end effector remains unchanged by adjusting the movement posture of the manipulator. In this way, the actual working state of the end effector is simulated. In addition, by installing the Kinect vision processing system, the path planning of the transplanting manipulator enables it to intelligently avoid obstacles.

To reduce damage to seedlings during the transplanting process, in addition to using the inclined transplanting manipulator, the principle of visual processing is used to avoid obstacles (Li *et al.*, 2021). During the transplanting process, to complete intelligent obstacle avoidance, the main information collected is the height information of the seedlings and edge information of the seedlings (Singh and Moses, 2021). By consulting the data (Sun, 2009), the Kinect vision processor developed by Microsoft is selected.
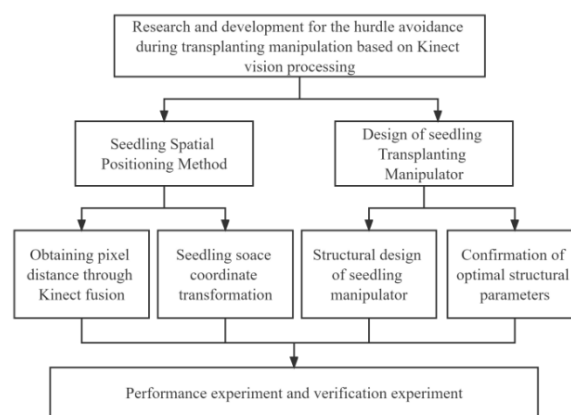

Fig. 1: Research process flow chart

Fig. 2: Planting pepper seedlings in plug trays

Kinect Vision Processor

In this design, Kinect1.0 RGBD vision processor is used which is shown in Fig. 4, which contains two depth-sensing cameras and one RGB infrared camera and its stable and effective sensing distance is 500~4000 mm (Sawant *et al.*, 2020). Two depth-sensing cameras can complete the collection of seedling height information. The RGB infrared sensor camera can complete the collection of seedling edge information. The collected information is transmitted to the PC through Kincet's dedicated data cable through the conversion connector and processed by Kinect Fusion on the PC side.

Kinect Vision Processing System

To completely process the information obtained by the Kinect vision processor, this experiment uses the Kincet Fusion vision processing system which is shown in Fig. 5 (Allah and Eid, 2020). The system first obtains an RGB image with depth information through a depth camera, establishes a spatial coordinate system with the camera coordinates as the origin, and calculates the position of the point cloud voxel in the spatial coordinate system (Gao *et al.*, 2019), which is shown in Fig. 6. Then, the position and posture of the seedlings are calculated according to the point cloud coordinates calculated from the pixel position of the current RGB image and the point cloud coordinates predicted in the previous image and a total coordinate system is established. Then, the truncated SDF (TSDF) value is then updated according to the seedling position and posture and analyzed together with the point cloud. Finally, the spatial information of key pixels is obtained according to the TSDF value. The SDF value describes the distance from the point to the surface, 0 on the surface, positive on one side of the surface, and negative on the other. The TSDF is changed regarding the most recent SDF value. If the maximum value of the nearby area is maxed truncation, then the actual distance is normalized by dividing by the value of max truncation, so the value of TSDF is between -1 and +1. First, each voxel is projected onto the camera according to the calculated spatial state of the seedlings. If the camera can get its information, there will be a pixel corresponding to it. Di(p) is the actual measurement value of the pixel from the surface, ti-vgti-vg is the distance from the voxel to the camera and the difference between Di(p) and ti-vgti-vg is the SDF value. In this experiment, the coordinate system established based on Kinect's machine vision principle is used as the overall coordinate system and the TSDF value is derived as the main parameter for obstacle avoidance in the vertical direction (Chen *et al.*, 2020). According to this parameter, the actual spatial position of the seedlings is obtained and this information is used as a working parameter to control the end effector to

realize the action of picking seedlings. So far, the establishment of the seedling space information acquisition system has been completed.

The information data are transmitted to the industrial computer through the optical cable which is shown in Fig. 5 and the industrial computer passes through the previously established coordinate system. The edge information and height information are processed; then, the path of the seedling picking device is planned to avoid obstacles (Kuş, 2021).

Seedling Device Design

At this stage, shovel-type, needle-type, and horseshoe-type end effectors are mainly used in the process of seedling transplanting at home and abroad. Compared with the needle type transplanting manipulator, the shovel type and the horseshoe type are larger in size and use a large structure to completely take out the substrate, but they take up more space and are not suitable for parallel installation. The needle-type transplanting end effector is small in size, simple in structure, and more reliable in work. In this experiment, since the design of the manipulator is for the performance test of the side-by-side seedling picking device in the later stage, the needle-type seed picking device is used in this experiment to facilitate the optimization of the structure of the end effector in the later stage.
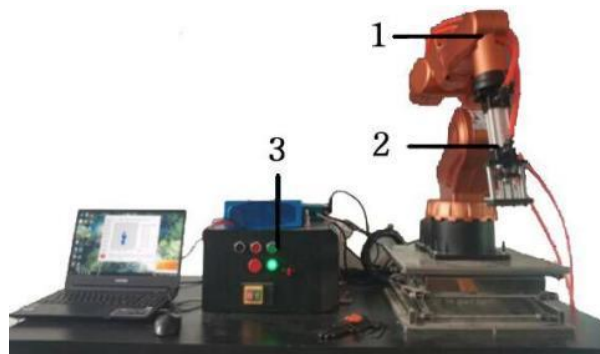

Fig. 3: Transplanting manipulator test platform1. WY760A manipulator; 2. The end effector of seedling picking device; 3. Industrial computer

Fig. 4: Kinect1.0 RGBD vision processor depth-sensing camera, RGB infrared camera, depth-sensing camera
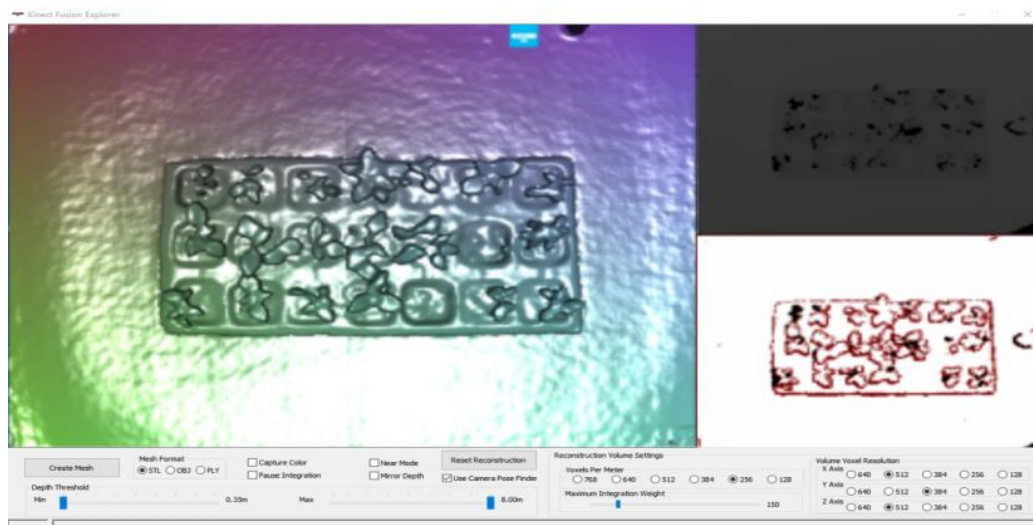
Fig. 5: Kinect fusion vision processing system

During the experiment, 21 seedling trays were selected as the culture container. According to the content of the reference (Abbasi *et al.*, 2021), the depth of the end effector inserted into the substrate was about 70-80% of the total depth during the transplanting process. Therefore, the total length of the end effector is 55 mm. According to the friction parameters between the substrate and the end effector, stainless steel was selected as the material of the end effector. In the transplanting process, to facilitate the seedlings to be separated from the end effector and not interfere with other actions, the size of the fixed block of the seeding needle is 15 * 20 mm. The axonometric view of the transplanting manipulatoris shown in Fig. 7.

Results and Discussion

Analysis of Factors that Affect the Seedling Performance

Through the force analysis of the seedling removal process of the seedling transplanting end effector, the penetration depth d of the seedling removal needle, the inclination angle α of the transplanting manipulator, and the insertion point distance L between the end effector and the edge of the plug tray will affect the end effector. The force analysis of the end effector on the seedling is shown in Fig. 8. According to the previous design dimensions of the end effector, the total length of the needles is about 70-80% of the depth of the hole. If the length of the needles is too short, the friction force between the substrate and the needles is too small to extract the seedlings. If the length of the seedling needle is too long, it will cause the seedling needle to contact the bottom of the seedling tray and damage the seedling tray. Therefore, the length of the seedling needle ranges from 45mm to 60mm. The tilt angle α of the end effector is analyzed according to the

length and depth of the steel needle. When the inclination angle is less than 10°, the friction force cannot be generated between the seedling-taking needle and the substrate, resulting in the inability to complete the seedling-taking action. When the inclination angle is bigger than 16°, the seedling needle will pierce the side of the hole during the insertion process, so the inclination angle is selected as 10°~16°. According to the assumption of ideal seedling picking conditions, when the distance between the end effector and the edge of the hole is greater than 14 mm, the fixing device of the seedling picking needle will contact the stem of the seedling, causing the stem to bend. Therefore, the insertion point distance is 10~16 mm.

Transplanting Test Evaluation Index

The seedling transplanting quality is generally evaluated by the integrity of seedling stems, leaves, and substrates. According to the analysis of the seedling transplanting quality, the completeness of the seedling leaves, the bending angle of the stem, and the damage of the substrate were used as the experimental evaluation indicators. During the transplanting process, the stem will automatically recover after a small degree of bending. According to the reference material, when the stem bending angle of the seedling reaches more than 20°, the elastic deformation will become plastic deformation, making the stem bend permanently (Werner *et al.*, 2015). Therefore, the degree of stem bending should be the specific gravity exceeding the stem bending as an evaluation index. According to the reference data (Jin *et al.*, 2018), these three indicators have the same proportion in the evaluation of transplanting, so this experiment proposes the transplanting quality parameter TQP (Transplanting Quality Parameter) and its calculation formula is as follows:

$$TQP = \frac{\frac{V_{R1}}{V_1} - \frac{Q_B}{Q} - \frac{V_{R2}}{V_2}}{3} \times 100\% \qquad (1)$$

where:
V_{R1} = Leaf area after transplanting
V_1 = Leaf area before transplanting
Q_B = Number of seedling stems tipped over 20°
Q = Total number of transplants
V_{R2} = Substrate cross-sectional area after transplanting
V_2 = Substrate cross-sectional area before transplanting

Analysis of the Performance Test Results of the Seedling Picking Device

According to the force analysis of the seedling end effector, the inclination angle of the end effector α, the depth of inserting the seedling needle into the substrate, and the distance between the end effector and the edge of the hole l are taken as three influencing factors and the transplanting quality parameters are used as the evaluation of transplanting quality. The evaluation mark and the factor level table are shown in Table 1.

Before each group of tests, the manipulator was adjusted to make the transplanting manipulator reach the test demand position to satisfy the test demand. Then, the air pressure of the air compressor was adjusted and the cylinder movement speed was adjusted to 1 m/s through the solenoid valve on the air compressor. In each group, 7 seedlings from 21 plugs were selected for the test at the beginning of the test. By controlling the position and posture of the transplanting manipulator, the end effector can maintain a fixed posture during the working process, so that its working state is the same as that of the side-by-side seedling transplanting equipment. According to the edge information of the plug tray and height information of the seedlings, a coordinate system was established so that the distance between the edge of the manipulator and the farthest end of the leaves is a suitable fixed value to avoid obstacles in the process of picking seedlings. Then, the Z-axis coordinate of the manipulator is changed so that the top of the seedling picking device has the same height as the plug tray. Finally, the manipulator is stretched forward to make the seedling picking device reach the appropriate position for picking. The seedling-taking needle was extended to take the seedlings; then, the manipulator was raised under fixed coordinates of the X and Y axes, so that the bottom of the removed seedlings was higher than the top of the seedlings that had not been removed and the entire process of seedling removal was completed. The Transplanting process of the transplanting manipulator is shown in Fig. 9.

Before carrying out the seedling transplantation performance experiment, the leaf area of the seedling was recorded with a camera and a vernier caliper and the bending angle of the seedling stem was measured with a protractor. After the seedlings were transplanted, a vernier caliper was used to obtain the cross-sectional area of the substrate and the area of leaf damage, and a protractor was used to record the bending angle of the seedling stem. Add a time recording program on the industrial computer to record the seedling transplanting time. Then, the transplanting quality parameters were calculated according to the formula. Vernier calipers were used to measure the depth of penetration d and distance of the insertion point l and the inclination angle a was measured by an optical goniometer (Karavasilis and Tsakiroglou, 2019). Each set of data was measured three times and the average value was taken as the final measurement data. The test data are shown in Table 2.

According to the three main factors, a three-factor four-level orthogonal test was designed and variance analysis was performed. By deriving the data in Table 3, all three factors are significant, the order of significance of each factor is $\alpha > d > l$. The experimental results are consistent with the previous mechanical force analysis results. According to the observation of the experimental process, the inclination angle directly affects the force exerted by the seedlings on the substrate during the transplantation process, so it has the strongest significance, while the distance and insertion depth mainly affects the position of the manipulator, so the significance is slightly smaller (Msukwa *et al.*, 2019). According to the measured data of 112 groups, when the depth of the seedling needle inserted into the substrate is 54 mm, the distance between the end effector and the edge of the hole is 10 mm and the inclination angle of the end effector is 12°, the seedling end effector will cause the least damage to the seedlings. When the seedling end effector is working, the damage rate to the seedling leaves is 4.70%, the bending degree of the stem is 16.67%, the remaining amount of the substrate is 83.45% and the quality parameter of seedling transplanting is 87.36%. The single transplanting time is 8.32±0.4s.

Fig. 6: Obtaining pixel distance through Kinect fusion
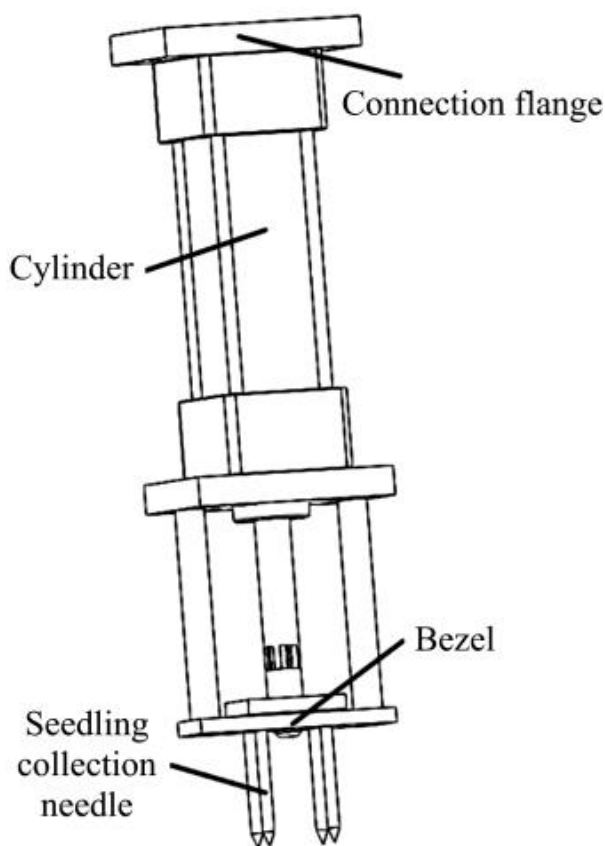
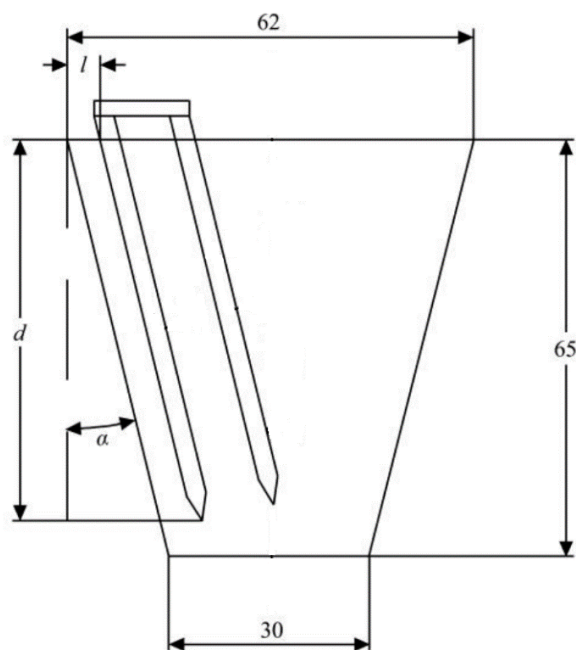**Fig. 7:** Axonometric view of the transplanting manipulator

Fig. 8: Design diagram of the performance parameters of seedling needles

Fig. 9: Transplanting process of the transplanting manipulator

Table 1: Factor level

	Natural variables		
Levels	d/mm	l/mm	α/°
1	44	8	8
2	48	10	10
3	52	12	12
4	56	14	14

Note: d is the penetration depth of the seedling needle; α is the inclination angle of the seedling needle; *l* is the distance of the insertion point

Table 2: Experimental scheme and results

	Natural variables			Transplanting quality
Number	d/mm	l/mm	α/(°)	parameters/%
1	1	1	1	56.72
2	1	2	3	87.36
3	1	3	4	72.40
4	1	4	2	75.43
5	2	1	4	82.09
6	2	2	2	50.80
7	2	3	1	60.13
8	2	4	3	83.33
9	3	1	2	79.87
10	3	2	4	81.14
11	3	3	3	82.56
12	3	4	1	81.86
13	4	1	3	72.36
14	4	2	1	52.36
15	4	3	2	69.72
16	4	4	4	75.63

Compared with the performance in other studies, according to the evaluation index of this experiment, the TQP index of the manipulator designed by Qizhi *et al.* (2018) reached 84.50% and the TQP index of the whole row of seedling picking manipulator designed by Cui *et al.* (2019) reached 86.20%, in contrast, the TQP index of this experiment was higher and the damage to the seedlings was lower. However, the seedling picking time in this experiment was relatively long and the working path needs to be improved in future research.

Table 3: Analysis of variance table

Source	Quadratic sum	df	Mean square	F value	Statistical significance
Model	1580.493	9	175.610	14.808	<0.01
Penetration depth d	609.732	3	203.244	17.138	<0.01
Distance of insertion point l	362.475	3	120.825	10.188	<0.01
Slope α	958.286	3	319.429	26.936	<0.01
Error	71.155	6	11.859		
Total	3579.141	15			

In this study, the seedling transplanting end effectors were improved, and combined with the seedling positioning method based on Kinect machine vision, the working path of the seedling transplanting manipulator was planned in real time to improve the integrity of the seedlings. The obstacle avoidance transplant of seedlings is realized.

Conclusion

To solve the problem of damage to the seedlings caused by the seedling end effector during the transplanting process, a transplanting method was designed in which the seedling transplanting end effector cooperated with the Kinect machine vision system. The spatial position information of the seedlings is obtained through the Kincet machine vision system and then the spatial information is used as reference data to control the end effector to achieve low-damage seedling removal.

Aiming at the performance design experiment of the seedling transplanting end effector, transplanting quality parameters were proposed to evaluate the damage caused by the end effector to seedlings. According to the experimental data, under laboratory cultivation conditions, when the insertion depth d is 54 mm, the insertion point distance l is 10 mm and the inclination angle is 12°, the seedling transplant end effector causes the least damage to the seedlings. According to the measurement, the single transplanting time of the end effector is 8.32±0.4 s. This design can provide a theoretical basis for low-damage transplantation of seedlings.

In the future, the following areas still need improvement:

(1) During the image acquisition process, it is found that the color of the RGB image obtained by this method will have a certain distortion rate and the seedlings within the range cannot be fully identified. Therefore, the overall lighting conditions need to be improved in the subsequent improved design

(2) Since the camera and the slide rail are rigidly connected, the vibration generated by the motor will cause a small change in the position of the camera during the seedling transportation process. Therefore, in the follow-up improvement, a stronger camera fixing device should be added to the camera

Author's Contributions

Kaikang Chen, Yanwei Yuan, Bo Zhao and Liming Zhou: Designed and performed the experiments, analyzed the data, and prepared the paper.

Kang Niu, Minghan Xu and Changwei Wang: Participated to collect the materials related to the experiment.

Xin Jin, Ruoshi Li and Yongjun Zheng: Designed the experiments and revised the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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