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RESEARCH ARTICLE

Design and Experiments of a Vision-Guided Integrated Cavity Tray Seedling Culling and Replanting System

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ABSTRACT Greenhouse seedling facilities have become a major method for modern vegetable production. In the process of raising seedlings, culling and replanting of cavity seedlings are essential to ensure the quality of the cavity seedling output. However, the process of culling and replanting is complex, traditional manual work is intensive and inefficient, and existing mechanized equipment is relatively homogeneous and low in intelligence. In this study, an integrated culling-replanting system based on visual guidance was developed to address these issues. It allows for real-time feedback of equipment operation information through the human-machine interface, culling and replanting of unqualified holes, and detection of culled seedling growth information. Further prototypes were built and culling and replanting trials were conducted. The results of the trials showed that the average success rates of culling and replanting were 93.00%, 83.07%, and 76.95% for culling and replanting with hole sizes of 21, 32, and 50, respectively. The average survival rates after surgery were all above 95.00%. The designed vision-guided integrated culling and replanting system is stable in operation, compact, has a strong human-machine interaction, and has a high transplanting success rate, which can effectively solve the problems of high intensity and low efficiency of culling and replanting operations in the culling and replanting processes, improve the intelligence level of the replanting equipment, and meet the actual operational requirements of the seedling breeding process.

INDEX TERMS Culling and replanting, facility seedlings, integration, machine vision, transplanting system.

I. INTRODUCTION

Seedling transplanting has been widely used in agricultural production, as it effectively shortens the time and improves the efficiency of seedlings [1], [2], [3]. However, to ensure the quality of seedlings, they must be strictly controlled during the nursery process [4]. To meet the growing space and nutrient requirements of cavity seedlings, it is often necessary to transplant high-density seedlings into low-density cavity trays [5], [6]. Therefore, the most relevant research is also based on this need, using industrial robots as the main body to perform cavity tray seedling transplanting operations by installing seedling picking claws at the end of robotic arms as actuators [7], [8]. Numerous researchers and companies have developed automated and efficient transplantation machines. For example, Dutch greenhouse pot flower production uses a transplanting machine with 30 transplanting jaws with various modes of operation, such as transplanting seedlings to pots and cavity trays [9]. The VISSER GR-2700 high-speed rice transplanting machine is equipped with 24 claws and has an average transplanting efficiency of up to 35,000 plants/h [10]. In addition, Ndawula et al. [11] developed a three-degree-of-freedom multijaw transplantation robot that can transplant six seedlings simultaneously in 1.8 seconds. Tian et al. [12] designed an automated cavity tray seedling transplanting machine to thinly transplant high-density cavity tray seedlings, with a productivity of 1800-2400 plants/h. Tong et al. [13] developed a transplanting mechanism with multi-jaw picking and sparse transplanting

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of hydroponic leafy vegetables. Optimal operating parameters were selected, and the transplanting efficiency was 3956 plants/h. Zhao et al. [14] improved the seedling transplanting actuator and designed a two-degree-of-freedom five-bar mechanism for the multipoint picking and single-point planting of flower seedlings. To improve the automation and efficiency of greenhouse seedling transplantation, Hu et al. [6] used a two-degree-of-freedom parallel mechanism and pneumatic manipulator to plan spot picking for seedling planting. However, the failure rate of cavity seedlings exceeds 15%, owing to seed quality, nursery environment, and sowing quality. If the quality of seedlings is not controlled, the subsequent mechanized transplanting operation and seedling sales price will be significantly affected [15], [16], [17], [18]. Therefore, the production of high-quality seedlings is important for subsequent transplantation.

To produce high-quality trays of seedlings, it is necessary to remove unsuitable trays from the nursery and replant healthy seedlings in their place. The use of manual work has problems, such as low efficiency, high cost, and errors. With the increase in the number of young rural people leaving the country and the aging of the population, the use of automated culling and replanting operations is important to reduce the economic loss of seedlings, improve the success rate and efficiency of subsequent planting, and is a trend for future development [19], [20]. With the development of mechanical automation technology, research has been conducted domestically and abroad on the sorting, culling, and replanting of unqualified cavity trays.

To enhance the intelligence of the transplanting process and reduce the injury rate of the seedlings, a visual inspection system has been added to the transplanting process, which enables the non-destructive detection of the growth information of the seedlings, aids the staff in the management of the seedlings, and helps guide the equipment in the sorting operation, providing accurate management of the transplanted seedlings [20], [21], [22], [23], [24], [25], [26], [27]. With the application of deep learning techniques in computer vision, new tools are available for intelligent extraction of information from cavity seedlings. Kolhar et al. [28] used a deep learning model for phenotypic analysis of Arabidopsis plant images with high accuracy for germplasm classification. Perugachi-Diaz et al. [29] used convolutional neural networks to classify images of cabbage seedlings, accurately classifying 94% of seedlings in the test set, with the trained deep learning model predicting whether the seedlings had grown successfully. A deep learning model can be deployed as an early warning tool to help professionals make important decisions and provide assistance in automated operations. Namin et al. [30] used deep learning models to classify plants and study their growth and dynamic behavior. Zhang [31] used machine vision to identify cavity tray seedlings, and designed a fully automatic transplanting machine control system. Jin et al. [16] used a deep learning model to classify lettuce seedlings and provide technical support for selective transplantation. Zhao et al. [32] used a deep learning model to quickly and accurately complete the task of classify cavity tray seedlings during transplanting operations. The use of deep learning models to detect vegetable seedling growth information is highly accurate and important for subsequent culling and replanting operations. Yao et al. [33] researched a seedling tray positioning control method based on the fusion of dual sensing information to ensure the accurate positioning of seedling trays for delivery in automated transplanting, providing a technical guarantee for automatic transplanting machines to adapt to standard plastic seedling trays. Jin et al. [34], [35] developed a transplanting machine based on machine vision guidance to address the problem of high transplanting injury and damage rates, significantly reducing the injury rate and achieving a success rate of 94.90%. Feng et al. [36] developed a cavity tray seedling sorting prototype that enabled selective transplanting of healthy seedlings from the original tray to the target holes. Tong et al. [37] improved the efficiency of seedling replenishment through rational path planning based on a hydroponic leafy vegetable transplanting mechanism. Li et al. [38] designed a selective planting control system to select healthy seedlings for transplantation using visual guidance. Various grading and replenishment machines were developed by Visser, Flier, TTA, and Techmek. Visser's FIX-O-MAT and TIFS-III are special machines developed for replanting operations [8].

At present, to ensure the quality of cavity tray seedlings and the effect of mechanized transplanting operations, usually by manual sorting and replanting of cavity tray seedlings, or through the perception of the presence or absence of cavity tray seedlings, selective transplanting of seedlings, classification of weak and strong seedlings, and seedling nursery during the culling and replanting research. Foreign countries are mainly large-scale facilities for seedling nurseries, and transplanting equipment research and development investment is huge and expensive. Moreover, transplanting and replanting systems are independent of each other, the operation is more complex, and most of them are operated by professional and technical personnel. In contrast, although China's annual demand for seedlings is huge, the nursery facilities are mainly small and medium-sized, engaged in agricultural labor are mostly middle-aged and old people, and not suitable for operating complex equipment. Therefore, based on the specific needs of seedling rearing in small and medium-sized facilities, we designed an integrated system for cavity seedling rejection and replanting as follows:

1. To address the deficiencies in the nursery process of small and medium-sized facilities, we designed an integrated vision-guided cavity seedling culling and replanting system.

2. The system integrates seedling growth information detection, culling and replanting of unqualified cavity seedlings, and visual information monitoring.

3. The prototype culling - replanting test shows that the equipment sorting success rate and culling and replanting

efficiency are high, in line with the requirements of small and medium-sized facility seedling operations.

This paper proposes a vision-guided cavity tray seedling culling and replanting system based on culling and replanting functions, which is richer in function and simpler in operation. The equipment has a high sorting success rate, good culling and replanting efficiency, compact structure, and small footprint, and meets the requirements of small and medium-sized facility seedling operations. In addition, it also has a certain degree of intelligence, which is in line with the trend of intelligent agricultural development.

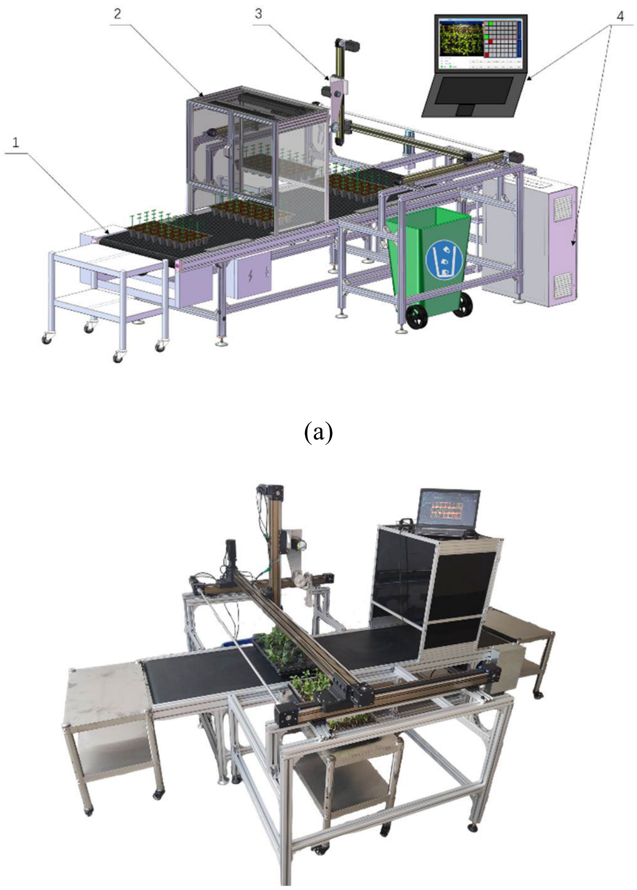
II. MATERIALS AND METHODS

A. GENERAL STRUCTURE

The control, conveying, information collection, culling, and replanting mechanisms comprise the vision-guided integrated culling and replanting system. The device's overall dimensions are 2.50 m in length, 1.70 m in breadth, and 1.60 m in height. It comprises four basic components. The control mechanism is the first, and it primarily consists of a computer, PLC, position sensor, and communication line for image processing and coordination control of the entire operation. The second component is the conveying mechanism, which primarily consists of a driving motor, directional guide rail, and conveying belt for moving cavity plates. The information-gathering mechanism comprises the following third component: It is primarily composed of an industrial camera and a lens that matches it, an acquisition black box, and a strip LED bulb used to capture images of the seedling. The culling and replanting mechanism, which constitutes the fourth component, primarily comprises an end-effector and XYZ linear module for precise culling and replanting of cavity trays.

B. SYSTEM WORKFLOW

The workflow of the vision-guided integrated culling and replanting system is as follows: The conveyor conveys the seedling tray from its initial position using a conveyor belt, which detects tray information and provides a trigger signal for the motor of the conveyor to start and stop, ensuring that the tray is in the correct position for detection, culling, and replanting. When the seedling tray is in the detection position, the camera in the information acquisition mechanism collects the image information of the seedling tray and transmits it to the host computer for image processing, which identifies the growth information of the seedling tray in each hole, then converts the one-dimensional data for storage and transmission, and transmits it to the controller through the communication cable, and at the same time triggers a signal to make the conveyor belt continue to run forward after the seedling tray to be operated is transported to the designated position, the conveyor mechanism stops, and the controller sends operating instructions to the culling- replanting mechanism, and the end-effector carries out the culling and replanting of unqualified holes.



(a)

(b)

FIGURE 1. Vision-guided integrated cavity tray seedling culling and replanting system: a. Three-dimensional view of the whole machine b. Physical view of the whole machine 1. Conveying mechanism 2. Information acquisition mechanism 3. Culling-Replanting mechanism 4. Control mechanism.

C. GROWTH INFORMATION TESTING OPERATION FOR CAVITY SEEDLINGS

1) IMAGE ACQUISITION

Image acquisition of cavity seedlings is a prerequisite for growth information detection. To capture high-quality images, the information acquisition mechanism used a Hikvision MV-CE200-10UC color camera with two long strips of Koma Vision LED on either side of the top camera on the acquisition box to ensure adequate lighting conditions. High-quality images are captured through the adjustment of camera height and focal length, and the captured image contains part of the conveyor mechanism, which is resized to a 2548 × 1277 pixels size cavity tray seedling image after Region of interest (ROI) cropping, followed by image preprocessing such as grayscale, OTSU threshold segmentation, removal of small noise points, and concatenation statistics, which reduces noise interference and enhances the image features of the target part. The whole acquired image cannot be directly used for deep learning model training, this paper aims to identify empty holes, poor quality seedlings, and healthy

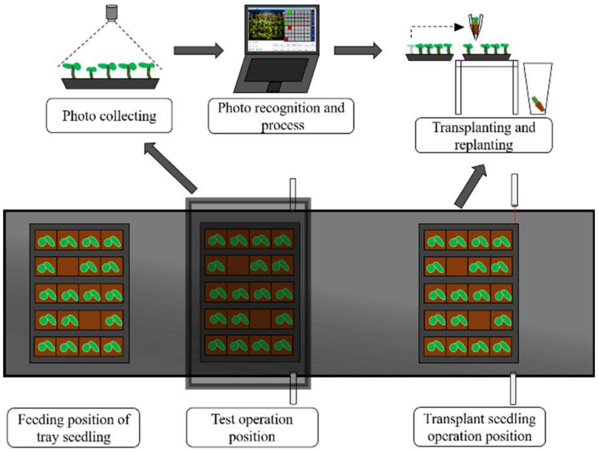


FIGURE 2. System workflow.

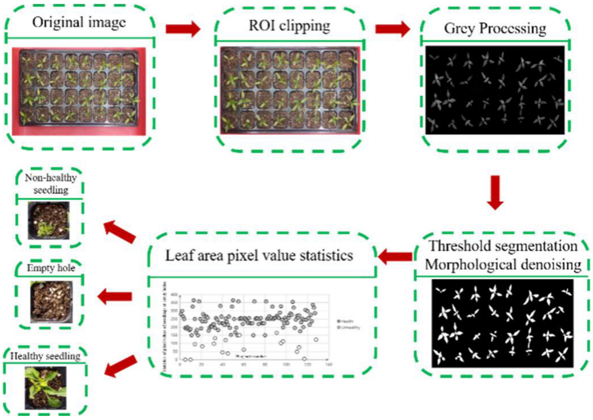


FIGURE 3. Construction of the dataset.

seedlings, therefore, the whole image is split into individual hole images and resized to a uniform size of 416 × 416 pixels' size. For image cropping the segmentation program is written based on Python language to split the image into individual images based on the distribution of pixel values of the seedlings in the cavity tray.

2) DATASET CONSTRUCTION

Datasets are critical for machine and deep learning, and high-quality, diverse datasets are more effective in solving real-world problems. The datasets are typically divided into three separate parts: training, validation, and test sets. The training set was used to adjust the model parameters based on the actual sample labels so that the model could accurately predict unknown information, the validation set was mainly used to adjust the model hyperparameters during training and monitor the convergence of the model, and the test set was used to check the model performance after the model was trained. To accurately construct the dataset of empty holes, poor quality seedlings, and healthy seedlings, the size of the leaf area pixel value of the acquired image was used as the basis to find the corresponding location of empty holes and poor quality seedling images, and dataset checking was carried out several times. In this study, the empty hole: leaf area value at the hole was 0; non-healthy seedling: leaf area at the hole was 0 to 100; healthy seedlings: leaf area value at the hole was greater than 100. Finally, 2,210 images of empty holes, 3,381 images of poor-quality seedlings, and 2,518 images of healthy seedlings were obtained.

3) IDENTIFICATION OF INFORMATION ON CAVITY SEEDLINGS

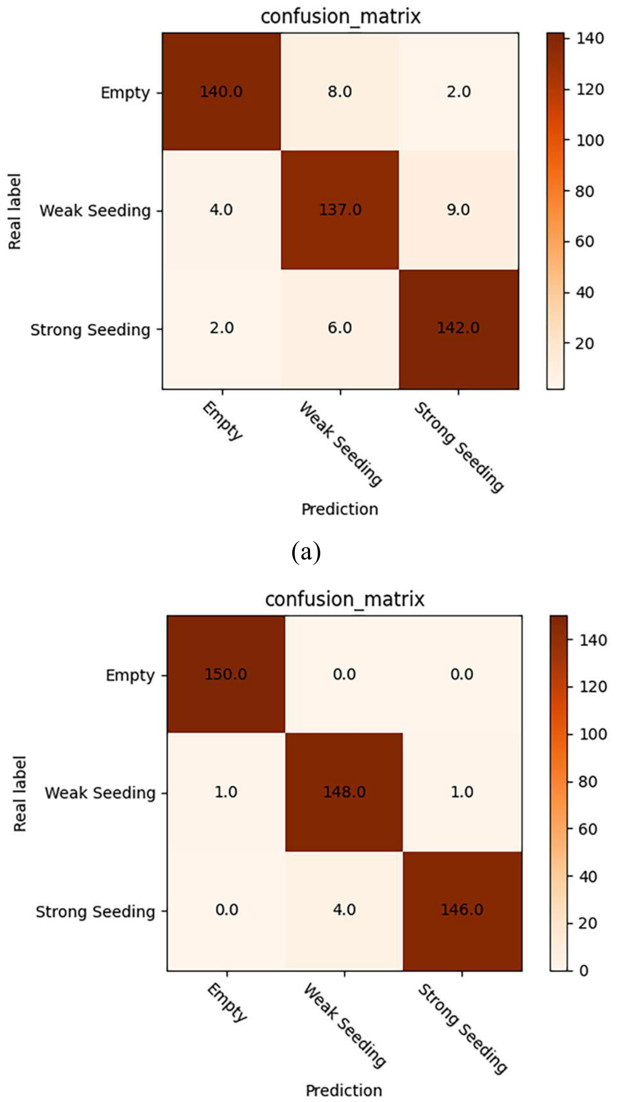
To realize the culling and replanting of cavity seedlings, the first step is to complete the screening of cavity seedlings, and the powerful feature extraction capability of convolutional neural networks is the preferred solution for image classification. We used the EfficientNet-B7-CBAM deep learning model, which was previously improved by our research team [39]. Convolutional neural networks are typically trained by increasing the image resolution, increasing the network width, or adding residual structures to deepen the network. EfficientNet uses co-tuning techniques to balance these three approaches. The core of the B7 model was a lightweight flipped bottleneck convolution module. MBConv modules contain SE modules, which allow the model to focus more on channel features and suppress unimportant redundant information. Although the SE module maximizes access to channel information, it cannot access the spatial feature information of the burrow seedlings, which affects the model's classification performance of the burrow seedlings to a certain extent. To acquire spatial information and improve the accuracy of the classification of burrowing seedlings, the CBAM attention mechanism, which mainly consists of a channel attention module and a spatial attention module, was introduced to obtain a good recognition effect with a recognition accuracy of 97.99% in the pre-test.

To further reflect the performance difference between the improved and original networks, the confusion matrices of the original and improved networks were compared. As shown in Fig. 4, the horizontal axis of the confusion matrix represents the predicted category labels, the vertical axis represents the true category labels, and the horizontal and vertical cross positions indicate the number of correctly predicted samples, with larger values indicating a better model performance. From the confusion matrix, it can be seen that the original network is easily confused in distinguishing between weak and healthy seedlings, while the improved network reduces the classification error rate, and at the same time, there is a great improvement in the average accuracy of the classification of empty cavities.

D. SEEDLING CULLING AND REPLANTING OPERATION

1) CULLING AND REPLANTNG OPERATION MECHANISM

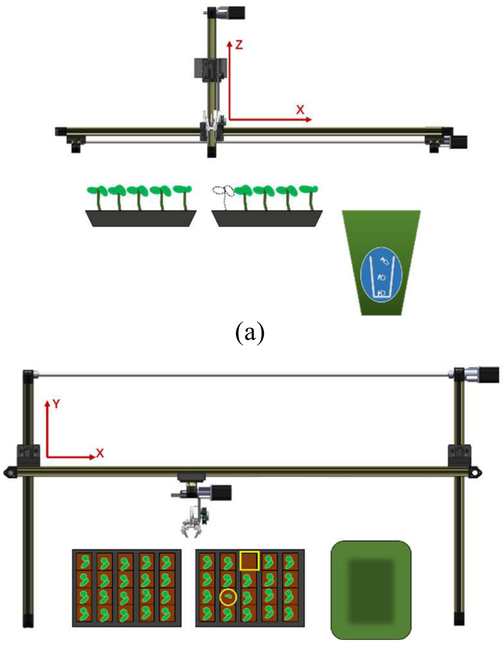
The culling-replanting mechanism is an important part of the machine, responsible for the culling and replanting of unacceptable cavity holes, which directly affects the quality and efficiency of the final operation. In this study, the



(b)

FIGURE 4. Confusion matrix for original and improved networks: a. Original network b. Improved network.

culling-replanting mechanism needs to have the ability to move, carry, lift, and automatically control, and simultaneously be as simple and compact as possible with a minimum of degrees of freedom. Therefore, a right-angle coordinate system structure is used, consisting of X, Y, and Z synchronous belt slide modules and end-picking jaws. The X-axis and Z-axis of the structure were set up on the Y-axis using a synchronous belt for transmission. The effective stroke of the horizontal movement of the X-axis synchronous belt was 1700 mm, effective stroke of the Y-axis synchronous belt operation was 500 mm, and effective stroke of the up-and-down movement of the Z-axis synchronous belt was 450 mm. The X-, Y-, and Z-axes are driven by a motor. To reduce costs and ensure accurate feeding, the drive motor was selected as a closed-loop drive motor, which can meet the requirements of the transplanting mechanism with a linear speed of up to 3 m/s.



(b)

FIGURE 5. Culling - replanting mechanism: a. Main view b. Top view.

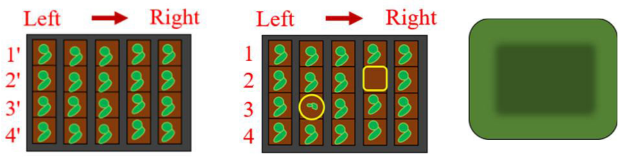
2) CULLING-REPLANTING PATH

The cull-discard-replant operation scheme was the starting point for the overall design of this study. In a cavity tray, the location of unqualified cavity holes is random; therefore, rational planning of the operating path of the cull-replant mechanism can effectively improve the efficiency of the operation. In this study, the culling and replanting mechanisms completed the culling, discarding, and replanting processes in one operation. The mechanism removes the unqualified holes in the order from row 1 to row 4 and from left to right in each row. Immediately after each rejection, seedlings were taken from the supply tray and replanted into the empty holes created by the removal, and from left to right in each row, from row 1' to row 4,' thus completing a rejection-replanting operation. The culling, discarding, and replanting cycles were repeated until all the unqualified holes in the tray were filled with healthy seedlings.

E. DESIGN OF THE CONTROL SYSTEM

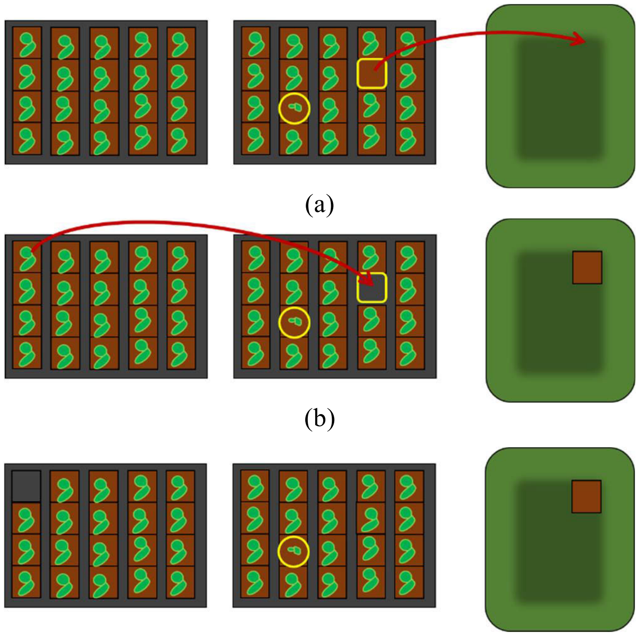
1) CONTROL SYSTEM DESIGN SCHEME

Several steps and processes are involved in the operation of the entire machine. As the control core of the equipment, it needs to be highly stable, capable of resisting interference, responding quickly, and coordinate the operation of various parts, such as culling-replanting, information collection, and conveying mechanisms. Simultaneously, real-time communication between each functional module and multiple servomotors and sensors requires signal acquisition



(a) (b) (c)

FIGURE 6. **Culling - replanting mechanism operating object: a. seedling supply trays; b. seedling trays to be operated; c. seedling discard box.**



(a)

(b)

(c)

FIGURE 7. **Schematic diagram of the seedling culling - discarding - replanting operation path: a. Culling operations b. Replanting operations c. Complete a single operation.**

and feedback, which results in a highly complex process. Therefore, a highly reliable and stable PLC controller is used for the entire machine. The workflow of the machine is that the conveyor belt will send the seedling tray to the corresponding workstation when the tray runs to the first sensor position, the sensor will transmit the information to the control system after detecting the seedling tray, at this time, the control system turns on the camera to collect and process the image of the seedling tray according to the feedback information, then the conveyor continues to run to the second sensor position, the sensor will transmit the information of the detected seedling tray to the control system. The control system stops the conveyor belt, and the culling-replanting mechanism starts to run, reaching a defined position under the control system to start the culling-discarding-replanting operation. Subsequently, the culling-replanting mechanism is reset, and the conveyor belt runs for the next operation. In this study, a cost-effective XINJE series XD3-32T-E PLC controller was selected. The movement of the culling and replanting mechanism in the direction of the X, Y, and Z axes was driven by the linear module motor model SL57S2112A-E1000 with a step angle of 1.8° and an operating torque of 3.8/N.m. The opening and closing of the mechanical jaws were also completed using motor model 57A3 with a step angle of 1.8° and an operating torque of 3.0/N.m. The sensor selected was a BF-M12JG -30 diffuse reflection laser sensor that was used to provide feedback on the position of the cavity disk.

2) CONTROL SYSTEM SOFTWARE DESIGN

The software system contains four modules: an image acquisition module, which calls the camera to collect images of seedling trays; an image segmentation module, which splits the trays into individual hole images according to different specifications; a hole-tray seedling classification module, which calls the trained algorithm to carry out feature extraction, extracts the information of empty holes, poor-quality seedlings, and robust seedlings, and outputs the classification results; and an information statistics module, which displays the completion of the culling and replanting operations. The main program of the software system consists of the following steps.

(1) Power on the machine and initialization of the device program. The conveyor motor rotates at the default speed for 2s, the proximity switch controls the X-axis, Y-axis, and Z-axis to return to the zero position.

(2) The conveyor motor speed was set, the speed of the closed-loop drive motor was set for the transplanting mechanism (X/Y/Z axis), and the preparatory work was completed before starting the whole machine.

(3) The cavity tray is fed into the system from the initial station, the conveyor belt transports the seedling tray to the image information processing position, the first position sensor detects the cavity tray, and the industrial camera is turned on for image acquisition of the cavity tray seedlings. At this time, the conveyor belt does not stop and continues to run forward while simultaneously completing image information processing and transmission to the industrial control machine.

(4) During the continuous operation of the conveyor, the second-position sensor detects the seedling tray when it is transported to culling and replanting stations. At this point, the conveyor belt stops, and the culling-replanting mechanism starts to operate, adjusting it to the calibrated position. The end robotic hand then descends to the optimum pick-up position, picking up the poor-quality seedlings and placing them above the discarded box for disposal. Next, the robotic hand was moved to the replenishment tray and dropped to the optimum position to pick up healthy seedlings and replant them in the tray to be worked on, completing the replenishment operation above the hole where the poor-quality seedlings were removed in the previous step. The robotic hand then rises and moves to the next poor-quality seedling to continue the picking, discarding, and replanting process. This process was repeated until the working trays had been filled with healthy seedlings.

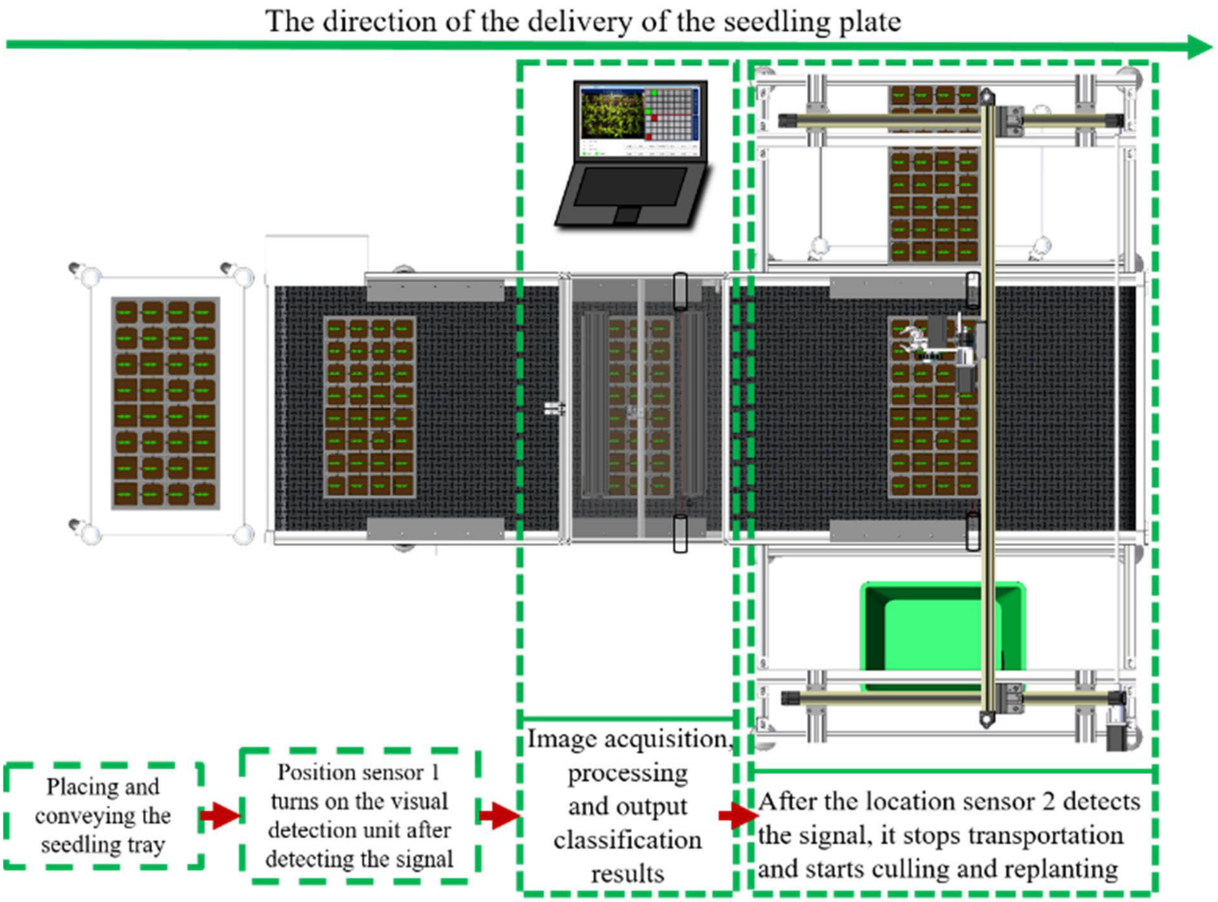


FIGURE 8. **The design scheme of the complete control system.**

(5) When the culling and replanting operations are completed, the culling-replanting mechanism returns to the X-, Y-, and Z-axis home points, the conveyor belt is activated, the cavity tray is sent to the exit, and the system automatically proceeds to the third step.

3) HUMAN-COMPUTER INTERACTION INTERFACE DESIGN

To intuitively obtain the information data of the cavity tray seedlings, the operating interface was designed based on PyQt and laid out using QTDesigner to collect, display, and store the operation and operational status of the device culling-replanting process, allowing the operator to have a timely and comprehensive understanding of the working status of the whole machine and facilitating the operation. The main interface includes four modules: control panel, parameter adjustment, image processing, and information statistics. The control buttons include algorithm tests, picture tests, mechanical settings, seedling tray settings, and camera settings.

III. EXPERIMENTS AND DISCUSSIONS

A. CULLING AND REPLANTING MECHANISM TEST

Pre-experimentation found that the water content of the substrate is one of the important factors affecting the physical properties of the seedling pile. The substrate water content affects the size of the substrate cohesion; within a certain range, the water content will increase the substrate and the adhesion of the hole tray, and the water content reduces the substrate adhesion between the reduced and not easy to form a complete substrate block, usually within a certain range of substrate water content; the higher the adhesion, the more favorable the mechanical claw to take the seedlings. Favorable to the mechanical claw to take seedlings when the water content is too high or too low will affect the transplanting machine performance; therefore, the comprehensive consideration of the substrate water content ranges from 44% to 66%. The seedling picking depth is the depth of the end-effector inserted into the substrate, which affects the firmness of seedling picking and degree of substrate removal. Combined with the size of the hole tray, the picking depth of the claw was in the range of 38–40 mm. In addition, the end-effector in the process of grasping and transporting the cavity tray seedlings may be owing to its own running vibration and the ability of the seedling pile to cause part of the substrate to scatter. From the module pre-running know, the module itself movement vibration of the greatest level of influence is the X-axis direction horizontal speed and Z-axis direction speed, the faster the vibration is greater,

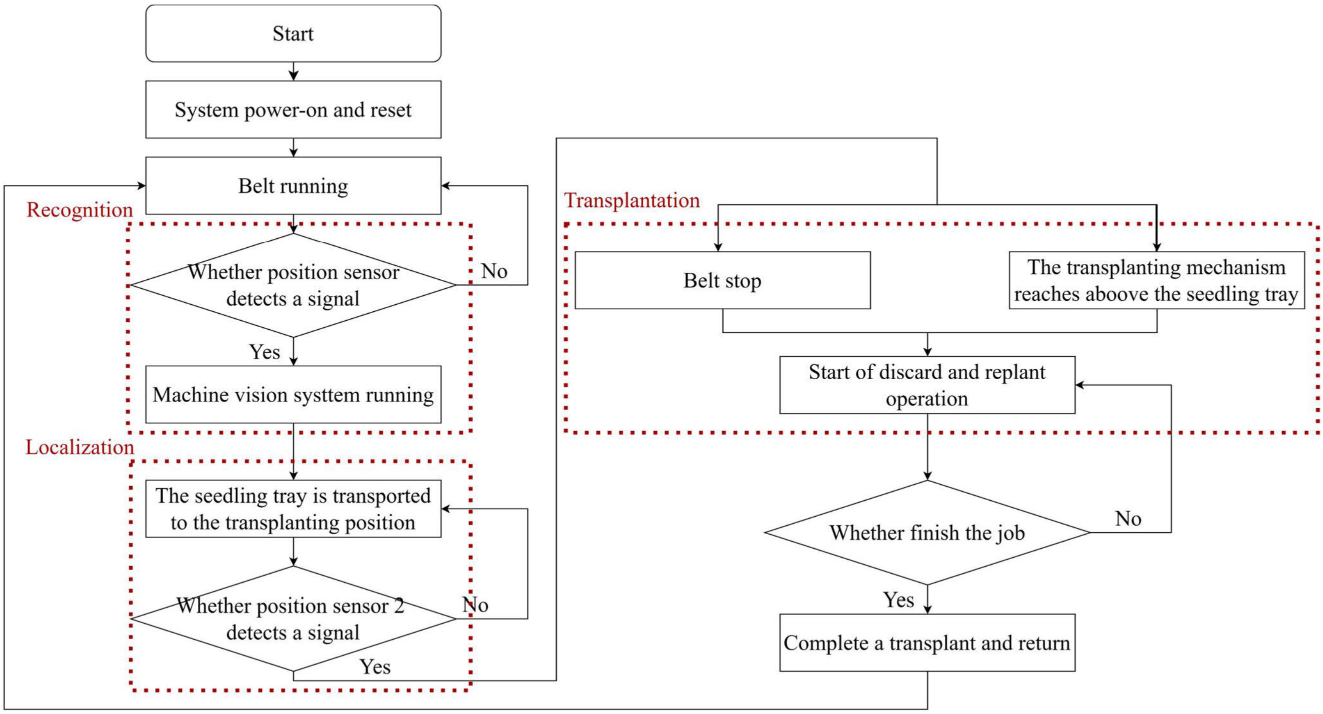


FIGURE 9. Schematic diagram of the main program design.

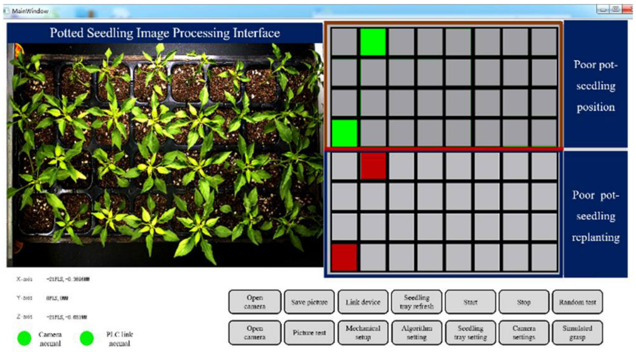


FIGURE 10. Human-computer interaction interface design.

resulting in mechanical claw clamping instability, resulting in the substrate off, under the comprehensive consideration, the X-axis movement speed range of 0.12 m/s to 0.40 m/s, the Z-axis movement speed range of 0.10 m/s to 0.30 m/s. Thus, in this study, the substrate water content, seedling taking depth, X-axis direction horizontal velocity, and Z-axis direction velocity were selected as influencing factors.

To investigate the influence of these four factors on the transplanting performance of the device and to obtain the best parameter combinations, a four-factor, three-level quadratic helix orthogonal combination optimization test was carried out with the four factors mentioned above as evaluation indices, and the influence of each factor on the transplanting success rate was analyzed by response surface analysis. The factor-level coding design used in this experiment is presented in Table 1.

TABLE 1. Experimental factor level coding table.

Level	X-axis velocity A/m/s	Z-axis velocity B/m/s	Depth of seedling extraction C/mm	Potting water content D/%
1	0.12	0.1	38.00	44.00
0	0.26	0.2	43.00	55.00
-1	0.40	0.3	48.00	66.00

Based on Design-Expert 8.0.6, for the experimental design and data processing analysis, the results of the regression equation analysis for the transplanting success rate are shown in Table 4.

The experimental data were analyzed using Design-Expert software to establish a quadratic polynomial regression equation between the horizontal velocity in the X-axis direction, velocity in the Z-axis direction, depth of seedling pickup, and water content of the seedling bowl as follows:

$$\begin{aligned} S = {} & 96.00 - 3.70A - 2.50B - 1.67C - 0.78D \\ & + 0.15A \cdot B - 0.47A \cdot C + 1.09A \cdot D + 4.06B \cdot C \\ & - 1.72B \cdot D - 1.41C \cdot D - 6.49A^2 - 4.38B^2 \\ & - 3.91C^2 - 1.02D^2 \end{aligned} \tag{1}$$

The results of this test were analyzed by variance analysis using the software, as shown in Table 2, where $P<0.05$,

TABLE 2. Regression model analysis of variance.

Indicators	Variance source	Sum of squares	Degree of free-dom	Mean square	F value	P value
S	Model	751.37	14	53.67	43.69	<0.0001
	Residual error	17.20	14	1.23		
	Lack of fit	13.62	10	1.36	1.52	0.3642
	Error	3.58	4	0.89		

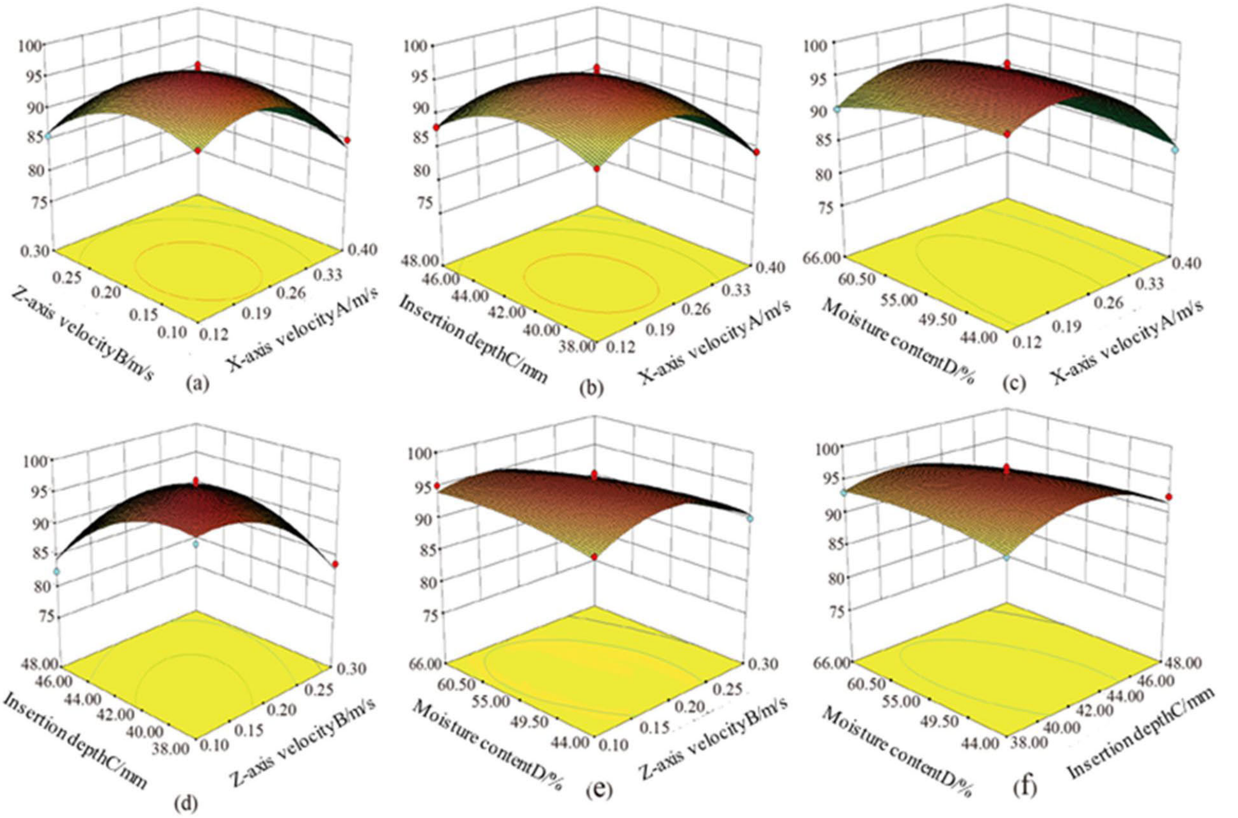


FIGURE 11. Response surface plots for different factors.

indicating significance, and P<0.001, indicating that the regression model was well fitted within the test range. The effects of each interaction factor on the transplanting success are shown in Fig. 11.

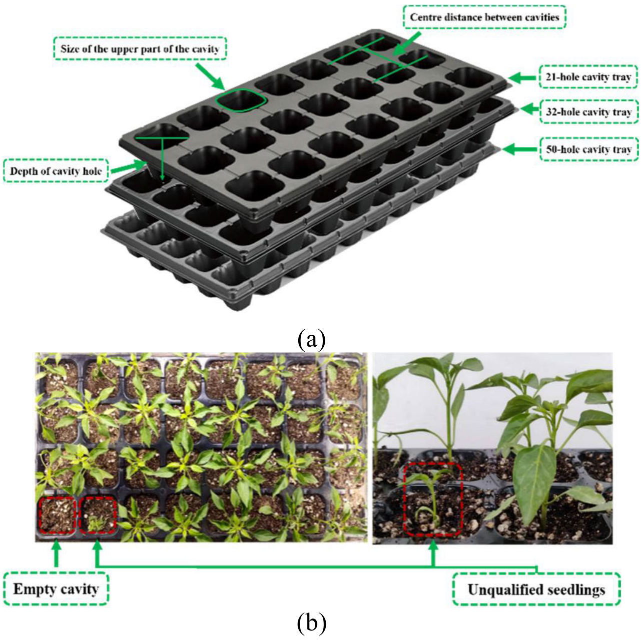
As shown in Fig. 11, the response surfaces of the different factors exhibited quadratic relationships and overall convex surfaces, showing a tendency to increase and then decrease. For example, Fig. 11a shows the effect of the interaction of X-axial velocity and Z-axial velocity on the transplanting success rate when the insertion depth and substrate water content are at the center level, and the success rate reaches the maximum value when the X-axial velocity A is 0.26 m/s and the Z-axial velocity B is 0.20 m/s. Fig. 11b shows the effect of the interaction of the X-axial velocity and insertion depth on the transplanting success rate when the moisture content of the substrate and Z-axial velocity were at the center level. When the insertion depth was certain, the transplanting success rate increased and then decreased with the increase of X-axial velocity, and reached the maximum when the X-axial velocity A was 0.26 m/s and the insertion depth C was 43 mm.

Using the Design-Expert software optimization solution module, we can find the parameters of the maximum transplanting success rate of picking and dropping seedlings to satisfy the constraints: The X-axial speed of the transplanting mechanism is 0.23 m/s, the Zaxial speed is 0.13 m/s, the mechanical claw picks up the seedlings at a depth of 40 mm, and the seedling bowl has a water content of 61%, and the seedling picking success rate under the combination of these parameters is 97.63%.

B. COMPLETE MACHINE TEST SCHEME

According to the operational requirements of culling and replanting, a prototype testbed was built, and the processing, assembly, and debugging were completed. The detection, positioning, culling, replanting, and overall performance of the system were evaluated using culling and replanting tests.

Luoxiao308 pepper seeds were used as the experimental material. The matrix was prepared in a 3:1:1 ratio of peat, vermiculite, and perlite, and the hole plates had 21, 32, and 50 standard holes. Temperature and humidity were determined using factory seedling standards, and cultivation was conducted for 21 days. Measurement tools, such as tape measures and soil moisture detectors, were prepared, and the experiment was completed at the Modern Agricultural Equipment Laboratory at the Xiyuan Campus of Henan University of Science and Technology.



(a)

(b)

FIGURE 12. Tray seedlings samples preparation: a. Standard cavity trays with 21, 32, and 50 holes b. 32-hole cavity tray seedling.

The main indicators used to evaluate the performance of the device were the culling success rate Q_1, replanting success rate Q_2, transplanting success rate Q, substrate breakage rate H, and seedling survival rate after replanting M. To verify the performance of the designed system, five trays of 21-, 32-, and 50-hole cavity trays were randomly selected from each sample, and the number of empty, poor quality, and healthy seedlings in the trays were recorded to facilitate statistical analysis of the information with the subsequent automated operation of the device. The calculation formula is as follows:.

$$Q_1 = \frac{S - S_1}{S} \times 100\% \tag{2}$$

$$Q_2 = \frac{S - S_2}{S} \times 100\% \tag{3}$$

$$Q = \frac{S - (S_1 + S_2)}{S} \times 100\% \tag{4}$$

$$H = \frac{m - m_1}{m} \times 100\% \tag{5}$$

$$M = \frac{N}{P} \times 100\% \tag{6}$$

where S denotes the number of failed seedlings in the cavity tray, S_1 denotes the number of culling failures, S_2 denotes the number of replanting failures, m denotes the total mass of potted seedlings used for replanting, m_1 denotes the total mass of potted seedlings after replanting, N is the number of live replanted seedlings, and P is the total number of seedlings in the tray. At the end of the trial, the replanted seedlings were marked and placed in an incubator with the temperature and humidity set for the planted seedlings, and then removed after three days to record the growth of the replanted seedlings.

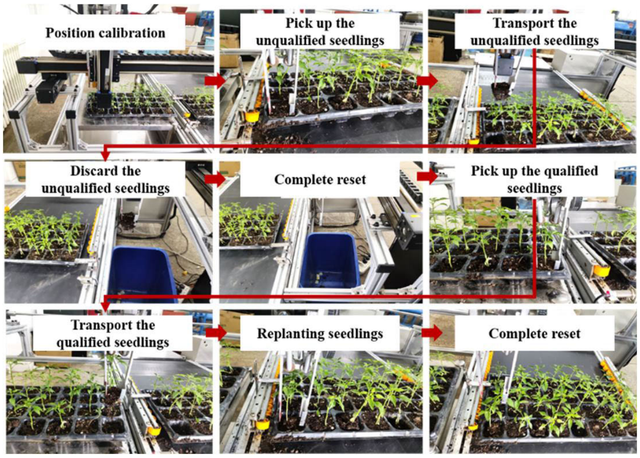


FIGURE 13. Operation steps of the test.

C. EXPERIMENTAL RESULTS AND DISCUSSION

As can be seen from Tables 4, 5, and 6, there were differences in the results of the culling-replanting tests with cavity trays of different sizes. The seedling survival rate (M) after transplanting achieved the desired results; however, the average transplanting success rate (Q) tended to decrease with an increase in the number of holes in the cavity trays, increasing from 21 to 50 holes, and the average transplanting success rate (Q) decreased by 12.55%. For the single picking and replanting operation times, motor overheating and vibration problems may occur during the transplanting process, resulting in a decrease in the transplanting efficiency of the device. Therefore, the motor speed range was increased by 20% from

TABLE 3. Compared to other similar studies.

Author	Recognition accuracy	The success rate of seedling extraction	Function
Li et al. [42]	89.14%	93.20%	Sorting and Transplanting
Zhang [31]	98.70%	97.50%	Transplanting
Kang et al. [43]	None	99.00%	Transplanting
Feng et al. [36]	90.00%	90.00%	Sorting and Transplanting
Our	**97.99%**	**97.63%**	**Sorting, Culling, and Replanting**

TABLE 4. Experimental design and calculation results.

Serial number	X-axis velocity A/m/s	Z-axis velocity B/m/s	Depth of seedling extraction C/mm	Potting water content D/%	The success rate of seedling taking S/%
1	0.26	0.20	43.00	55.00	95.00
2	0.40	0.20	43.00	66.00	83.75
3	0.12	0.30	43.00	55.00	85.62
4	0.40	0.10	43.00	55.00	85.00
5	0.12	0.10	43.00	55.00	91.87
6	0.26	0.20	43.00	55.00	95.00
7	0.26	0.10	43.00	66.00	95.00
8	0.26	0.20	43.00	55.00	96.25
9	0.26	0.10	38.00	55.00	95.00
10	0.26	0.10	43.00	44.00	92.50
11	0.40	0.20	38.00	55.00	84.37
12	0.12	0.20	38.00	55.00	90.62
13	0.26	0.20	43.00	55.00	96.87
14	0.26	0.20	48.00	66.00	88.12
15	0.40	0.20	48.00	55.00	80.00
16	0.26	0.30	43.00	66.00	85.62
17	0.12	0.20	48.00	55.00	88.12
18	0.26	0.20	38.00	66.00	93.13
19	0.26	0.10	48.00	55.00	82.50
20	0.26	0.20	48.00	44.00	92.50
21	0.26	0.30	43.00	44.00	90.00
22	0.12	0.20	43.00	44.00	94.37
23	0.26	0.30	48.00	55.00	87.5
24	0.26	0.20	43.00	55.00	96.87
25	0.26	0.20	38.00	44.00	91.87
26	0.40	0.20	43.00	44.00	83.75
27	0.12	0.20	43.00	66.00	90.00
28	0.40	0.30	43.00	55.00	79.37
29	0.26	0.30	38.00	55.00	83.75

the maximum single transplanting time of the cavity tray seedlings, that is, the maximum single picking and replanting time was $t_{\max} \times (1+20\%)$, which was calculated to be 5-6s. Further analysis of the main factors affecting the cull and replant test results and the transplanting efficiency are as follows:

(1) As the size of the hole decreases, information from the next hole is more likely to interfere with identification, and there are cases of misclassification. The misclassification of empty holes as poor-quality seedlings may be because of the presence of shed leaves and debris in the next hole. The misclassification of poor-quality seedlings as healthy may be due to the presence of leaves from the tray of seedlings in the next hole. The misclassification of healthy seedlings as poor-quality seedlings may be due to the angle of the equipment, tilted cotyledons of the cavity trays, and low resolution of the image.

(2) In the process of rejecting and replanting mechanical claws, some hole-tray seedlings are not rejected and replanted successfully, even though they have been fully recognized and positioned, which may be related to the end of the picking up of seedling mechanical claws. This may be due to the

TABLE 5. 21-Hole cavity tray seedling cull-replant experiment.

Specification of cavity trays	Test number	Number of failed cavities	Number not culled	Number of failed plantations	Q_1(%)	Q_2(%)	Q(%)	H(%)	M(%)
21	1	2	0	0	100	100	100	5.32	100
	2	4	0	1	100	75.00	75.00	8.56	95.24
	3	3	0	0	100	100	100	7.11	100
	4	5	0	1	100	80.00	80.00	10.63	95.24
	5	3	0	0	100	100	100	6.71	95.24
	6	2	0	0	100	100	100	4.15	100
	7	3	0	1	100	66.67	100	9.28	90.48
	8	2	0	0	100	100	100	5.06	100
	9	4	1	0	75.00	100	75.00	7.23	95.24
	10	1	0	0	100	100	100	2.97	100
		Average			97.5	92.17	93.00	6.70	97.14

TABLE 6. 32-Hole cavity tray seedling cull-replant experiment.

Specification of cavity trays	Test number	Number of failed cavities	Number not culled	Number of failed plantations	Q_1(%)	Q_2(%)	Q(%)	H(%)	M(%)
32	1	4	0	0	100	100	100	9.77	100
	2	8	1	1	87.50	87.50	75.00	12.23	96.88
	3	5	1	0	80.00	100	80.00	8.28	100
	4	5	0	1	100	80.00	80.00	14.89	96.88
	5	7	0	1	100	85.71	85.71	15.12	93.75
	6	5	1	0	80.00	100	80.00	10.18	96.88
	7	4	0	1	100	75.00	75.00	16.58	93.75
	8	4	1	0	75.00	100	75.00	11.09	96.88
	9	3	0	0	100	100	100	9.32	96.88
	10	5	0	1	100	80.00	80.00	12.15	93.75
		Average			92.25	90.82	83.07	11.96	96.57

mechanical claw structure being more complex, larger in size, and relatively large in weight, and the vibration generated by the operation of the mechanism caused by the broken seedling bowl, resulting in the failure of culling and replanting operations.

(3) The random distribution of unqualified holes in the cavity trays, sometimes with a large span of position, required the robot to run a longer path with the seedlings, thereby increasing the operating time for each operation. However, the high weight of the robot leads to excessive loads on the drive motor, which also affect the overall operational efficiency.

In addition, deep learning technology is rapidly developing, and the robustness of the model can be improved by data augmentation, such as geometric transformations (cropping and deformation), color transformations (noise and blurring),

TABLE 7. 50-Hole cavity tray seedling cull-replant experiment.

Specification of cavity trays	Test number	Number of failed cavities	Number not culled	Number of failed plantations	Q_1(%)	Q_2(%)	Q(%)	H(%)	M(%)
50	1	7	0	1	100	85.71	85.71	11.32	98.00
	2	6	1	1	83.33	83.33	66.67	10.26	96.00
	3	7	1	0	85.71	100	85.71	12.59	96.00
	4	9	1	2	88.89	77.78	66.67	24.02	92.00
	5	8	0	1	100	87.50	87.50	14.07	94.00
	6	5	0	1	100	80.00	80.00	10.94	98.00
	7	7	2	0	71.43	100	71.43	13.11	96.00
	8	6	1	0	83.33	100	83.33	12.03	96.00
	9	5	0	1	100	80.00	80.00	9.83	98.00
	10	8	1	2	87.50	75.00	62.50	13.49	94.00
		Average			90.02	86.93	76.95	13.17	95.80

and the use of generative adversarial networks (GAN) [40]. The model can also be lightweight by reducing the number of model parameters and improving its deployment in hardware devices [40], [41].

In order to further validate the advantages of the whole machine used in this study, we selected relevant devices studied by several scholars for a comparative analysis. From Table 3, we can see that the recognition accuracy rate of our equipment is 97.99, and the success rate of seedling picking is 97.63, which have certain advantages compared with similar equipment. Meanwhile, in terms of equipment function, our equipment has the functions of hole-tray seedling sorting, culling, and replanting. In terms of equipment operation, the equipment has an intuitive human-machine interaction system, which is easy to operate, while most of the other machines have only two functions of transplanting or sorting.

IV. CONCLUSION AND FURTHER WORKS

In this study, a vision-guided integrated culling and replanting system was developed for culling and replanting greenhouse seedlings, enabling integrated culling and replanting operations and visual monitoring of operational information. A prototype was built in the laboratory and culling and replanting tests were conducted on trays of different sizes to evaluate the performance of culling and replanting operations. The main results of this study are as follows.

(1) The designed visually guided integrated culling-replanting system includes an information collection mechanism, a conveying mechanism, a control mechanism, and a culling-replanting mechanism, which adds the function of replanting without increasing the size of the device in similar transplanting machines.

(2) To visualize the culling and replanting operations, a visual human-machine interaction system was developed to improve the information level of the device and simplify the operation.

(3) The bench test showed that the average survival rate of replanted seedlings was $>$ 95.00%. Under the same conditions, the culling and replanting results were best for the 21-hole tray size, with an average success rate of 93.00%, while the 50-hole tray size had a lower success rate than the pre-test results but still met the operational requirements given the complexity of the actual transplant.

(4) The detection and positioning speed of the entire machine can meet real-time requirements.

The designed integrated vision-guided culling-replanting system can therefore effectively cull and replant greenhouse-culled seedlings without damaging seedling growth, which is beneficial to the development of the vegetable industry and improves the quality of transplants during fieldwork. In future research, the influence of the actual environment will be considered and the prototype performance will be further tested in an actual planting environment. In addition, a lightweight seedling removal manipulator can be designed to improve the transplanting efficiency. A more efficient seedling culling-replanting path can also be planned, and force sensors can be added to the end of the manipulator to improve the intelligence of the equipment.

APPENDIX

EXPERIMENTAL DESIGN AND CALCULATION RESULTS

See Table 4.

APPENDIX

CULLING-REPLANTING EXPERIMENTS WITH DIFFERENT TYPES OF HOLE TRAY SEEDLINGS

See Tables 5–7.

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