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Design and Testing of an Intelligent Multi-Functional Seedling Transplanting System

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Abstract: Transplanting is a core part of factory nurseries and is a key factor in determining the healthy growth of seedlings. While transplanting has a single operational function, the complete process of sorting, transplanting and replanting is complex. This paper innovatively proposes an intelligent multi-functional seedling transplanting system, where the sorting, transplanting and replanting functions can be achieved with a single machine. This paper proposes the key strategies of seedling dynamic detection during transplanting and performing transplanting and replanting within the same tray, thus realizing the integration and miniaturization of the all-in-one machine. Then, through the flat design of the transplanting–replanting mechanism and the construction of a multi-module cooperative control strategy, a stable and reliable multi-functional synchronous operation is realized. Finally, the integrated operation experiment shows that the transplanting efficiency of the whole machine is 5000 plants/h, and the qualification rate after replanting is as high as 99.33%, which meets the operational needs of factory nurseries.

Keywords: tray seedlings; sorting–transplanting–replanting; multi-functional; all-in-one; collaborative operation

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1. Introduction

Factory nursery technology emerged from Europe and the United States in the 1970s. It is widely used for the cultivation of seedlings of various crops, such as vegetables and flowers [1]. The factory nursery mainly operates in plant factories or smart greenhouses; it can automatically control the temperature, humidity, light, and nutrients for high-quality seedling production [2]. Compared with the traditional nursery method, the factory nursery has the advantages of annual production, high seedling rate, fewer diseases and pests, and labor savings [3]. At present, the factory nursery is widely promoted and applied in many countries, such as the United States, the Netherlands, Germany, Italy, and Japan, and has become an important part of modern agricultural development [4].

Once the tray seedlings have grown to a certain size, they must be transplanted from high-density trays to low-density trays in order to promote further crop growth [5,6]. The Netherlands, Denmark, Australia, and Italy have been the site of numerous studies on the transplanting technology of seedlings in trays. Most of the early studies installed seedling picking claws on industrial robots, which have the advantages of high flexibility, high speed, and high accuracy; however, the low operational efficiency is not suitable for large-scale transplanting operations [7,8]. With the rapid development of automation technology, scholars and companies have developed mature multi-claw high-speed transplanting machines that can be used for transplanting operations in tray and pot seedings [9,10]. Kang et al. [11] developed a transplanter for young vegetable seedlings with an operating efficiency of 2800 pots/hour and a success rate of 99%. Ndawula et al. [12] developed a 3DOF multi-claw transplanting robot that can transplant six seedlings simultaneously in just 1.8 s. VISSER's GR-2700 ultra-high-speed transplanter is equipped with 24 claws and has an average transplanting efficiency of up to 35,000 plants/h [13]. TTA's PackPlanter 2230 transplanter is equipped with 30 independently controlled claws, and it has a transplanting efficiency of 60,000 plants/h. Transplant system's TEA-Transplanter is equipped with 8 claw-effectors and can transplant up to 14,000 plants/h [14].

During the nursery process, ungerminated, small, and weak seedlings often appear in the trays, and transplanting operations can also result in damage to seedlings [15,16]. This affects the quality of seedling growth in the tray after transplanting, thus reducing yields and causing waste. The ungerminated, small, weak, and damaged seedlings need to be discarded from the trays, and healthy seedlings from other trays are used for replanting [17]. Thus, automatic sorting and replanting equipment for cavity seedlings is important to ensure the quality and efficiency of transplanting and improve the subsequent healthy growth of seedlings. It has become a key technology and research hotspot in factory nurseries [18].

Since the 1990s, sorting machines have been developed and used in the production of tray seedlings for vegetables [19]. de Medeiros et al. [20] proposed an interactive and traditional machine-learning-based method for classifying soybean seedling quality; the model exhibited high performance for seedling classification, with an overall accuracy of 94% in the experiment. Otoya et al. [21] developed a leaf area estimation algorithm based on RGB-D images, which was effective for grading artichoke seedlings. Feng et al. [4] designed a flower transplanter, with a transplanting efficiency of 700–900 cycles per hour. Feng et al. [22] designed a sorting transplanter; the detection accuracy of high-quality seedlings of pepper was over 90%, and the measurement error of physical parameters of seedlings was around 5 mm. Tong et al. [23] designed a sorting machine that could automatically perform image correction of skewed trays and seedling quality inspection of trays with 200 holes by leaf area and leaf number features. Jiang et al. [24] developed a machine vision system for seedling growth detection in potting operations, and the results showed that the machine had good recognition accuracy for seedling trays of 10~15 day growth and good adaptability for different types of trays. All of the above sorting machines are photographed by CCD cameras looking down, thus acquiring the entire cavity tray image, which is then segmented and algorithmically processed. This is only applicable to tray seedlings that do not grow for a long period after sowing. In addition, detection under the condition of the leaves shading each other is extremely poor, so its application scope and operation effect are greatly limited. In an alternate application, seedlings are ejected through a small hole at the bottom of the tray; the camera acquires a leaf and stalk image through a side view, and the detection system determines seedling width and stalk uprightness information. Jin et al. [25] and Syed et al. [26] used the Intel Realsense D415 camera to acquire side images of cavity seedlings and performed image processing to obtain the height of the seedlings. The two methods of top view and side view can detect different physical size information of tray seedlings.

The coordinate information of detected ungerminated, small, and weak seedlings is sent to the picking unit in order to discard these non-healthy seedlings [27]. Meanwhile, the sorting machine sends information on the coordinates of the empty holes to the supporting replanting equipment for accurate and high-speed replanting operations [28]. In recent years, Visser, Flier, TTA, Techmek, and other companies have developed a variety of grading and replenishment equipment. For example, Visser's FIX-O-MAT and TIFS-III are special machines developed for replanting operations. At the same time, these companies have also developed transplanting–sorting or sorting–replanting integrated machines.

China's annual vegetable seedling production alone exceeds 800 trillion plants; the sorting, transplanting, and replanting operations are mainly carried out by hand, which is extremely labor intensive and costly [27]. The above transplanting, sorting, and replanting machines have been widely used in large factory nurseries in Europe and the US. However, Chinese factory nurseries are mainly of small and medium scale. There are issues in promoting the use of foreign transplanting, sorting, and replanting machinery in China:

(1) The foreign sorting, transplanting, and replanting machines are independent of each other but need to be used in conjunction with each other, resulting in a complex overall operational process. (2) The complete system is complex and large, requiring significant monetary investment and a large space. In addition, China tray standards often do not have a perfect fit with imported machines [22]. (3) The existing sorting machines are mainly oriented to detect the quality of seedlings before or after transplanting or replanting of trays, and only achieve the simple measurement of seedling presence or absence and the physical parameters of leaves; they cannot provide feedback on seedling damage caused during transplanting.

In recent years, Chinese researchers have worked to design an inexpensive machine that is appropriate for the domestic market [29,30]. Han et al. [31] developed a light and simple automatic transplanting machine with seedling picking claws to transplant in high-density and low-density trays at high speed, with an efficiency of 960 plants per hour. Based on block area matching, Harris corner point detection, and SURF feature point detection algorithms, Tong et al. [32] successfully developed a tray seedling grading system with 98.7% accuracy in detecting seedling health information. Zeng et al. [33] proposed a system to classify mica seedlings based on time series images, and the experimental results showed that the method could classify quickly and accurately compared with the pixel area-based classification method. Junhua et al. [34] developed a replanting system that sends information about the coordinates of the holes detected by the sorting machine to the replanting machine to control the robot to discard and replant unhealthy seedlings. He et al. [35] proposed a greedy genetic algorithm replanting system that optimized the replanting paths of sparse and dense cavity trays; the minimum replanting time for a single plant was only 1.81s. The above Chinese researchers designed machines operating with a single function, satisfying only one of the functions of transplanting, sorting, or replanting.

China has the following national conditions: (1) Most factory nurseries in China have a small footprint, while the foreign sorting, transplanting, and replanting lines are huge. (2) Due to the gap in seedling technology and greenhouse environmental control technology, the rate of strong seedlings in China is lower than that in Europe and the United States, and the economic efficiency of cavity tray seedlings is lower. This has led to the inability of nurseries to purchase expensive machines from abroad. (3) Farmers have insufficient professional and technical skills to operate advanced machines from abroad. This paper combines the specific needs of China to design a new intelligent multi-functional seedling transplanting system. The innovation proposes the key strategies of seedling dynamic detection during transplanting and transplanting–replanting within the same tray, thus realizing the integration and miniaturization of the all-in-one machine. Then, through the flat design of the transplanting–replanting mechanism and the construction of a multi-module cooperative control strategy, a multi-functional stable and reliable synchronous operation is realized. Finally, we successfully develop an integrated, compact, and low-priced multi-functional seedling transplanting system. Without changing the main structure and operation process of the existing transplanting system, the all-in-one machine achieves better operational results.

This paper is structured as follows: The all-in-one machine design methods are introduced in Section 2. In Section 3, we explain the control system of the multifunctional operation. In Section 4, we present the integrated operational performance of our multi-functional seedling transplanting system. Finally, a summary of this study is presented in Section 5.

2. All-in-One Machine System Design

2.1. Trays and Seedings

The production of good-quality tray seedlings is not only related to seeds and cultivation techniques but also is inextricably linked to the tray itself; thus, choosing the right tray is a prerequisite for successful seedling development. We have conducted much research on seedling species, tray specifications, and transplanting equipment requirements in factory nurseries in Jintan, Liyang, and Dongtai, Jiangsu Province, China.

In our interviews, we found that 105-hole and 50-hole trays are the most widely used in Chinese factory nurseries [36]. As shown in Figure 1, the high-density tray size selected for this study was 105 holes (7 × 15), and the low-density tray size was 50 holes (5 × 10), with single holes having a quadrilateral shape, and the trays made of polystyrene. The specification and quality of the trays conform to Chinese forestry standards (LY/T 2234-2013); detailed parameters are shown in Table 1 [37].

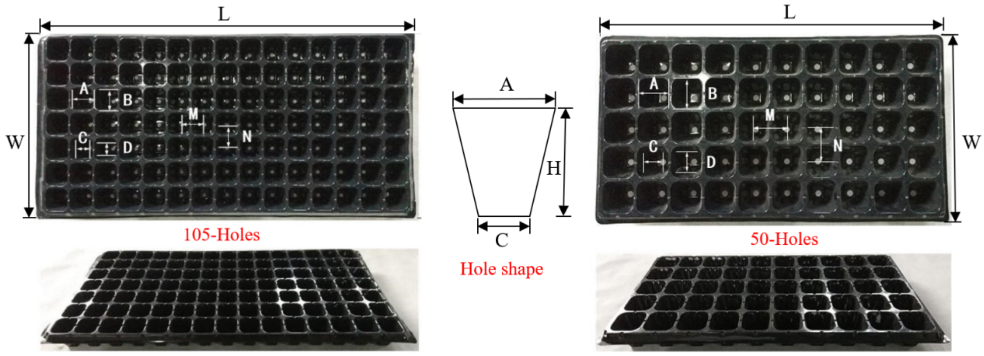


Figure 1. The 105-hole and 50-hole trays.

Table 1. Parameters of 105-hole and 50-hole trays.

Specification	Size L × W/mm	Center Distance M × N/mm	Hole Depth H/mm	Upper Port A × B/mm	Lower Port C × D/mm
105-hole	540 × 270	34 ×34	39	31.5 × 33	13 × 15
50-hole	540 × 280	51 × 51	47	46.5 × 46.5	19 × 19

According to the production research of factory nurseries, the main crops with high demand for cavity seedlings in China are cucumber, watermelon, tomato, and pepper. Cucumber seedlings have the lowest germination rate of these crops and are the most susceptible to damage of leaves and stalks [38]. Therefore, the selection of cucumber seedlings as the study object could better verify the reliability of the machine operation and also better respond to the replanting effect on the ungerminated holes. The existing standards in the field of transplanting in China are mainly for field crops, while the transplanting standards for greenhouse factory seedlings have yet to be developed [39]. We visited a number of factory nurseries and conducted research and interviews. We calculated that the height range of cucumber seedlings for transplanting operations is 80–120 mm, as shown in Figure 2.

Figure 2. Tray seedlings of cucumber.

2.2. Overall Scheme

According to the small, multifunctional, low-cost, and high-efficiency requirements of the predominantly small- and medium-scale factory nurseries in China, this paper designed an integrated and miniaturized intelligent multi-functional transplanting system, to solve the technical problems of integrated layout and the cooperative control of the multi-functional modules of sorting–transplanting–replanting. This all-in-one machine consists of two tray delivery modules, a multi-claw transplanting module, a single-claw replanting module, a seedling quality detection module, and a control system, as shown in Figure 3.

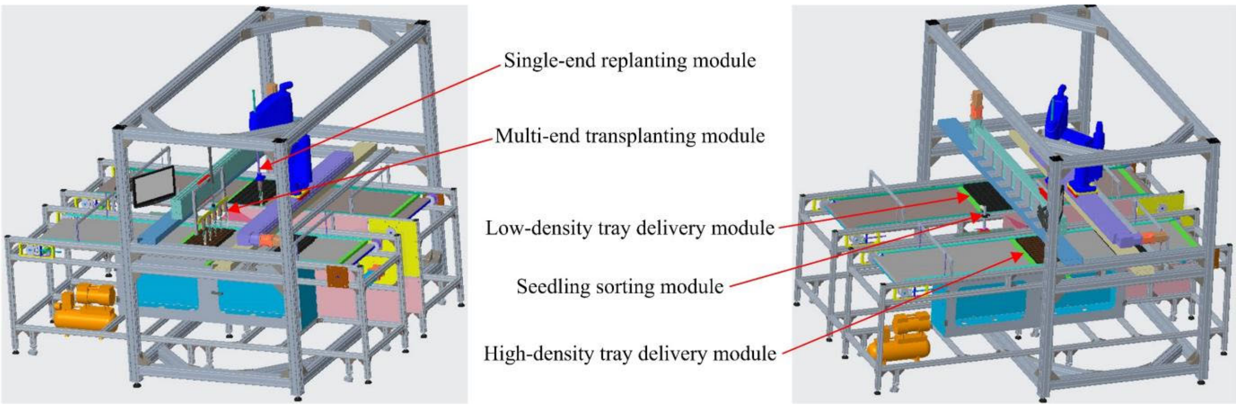


Figure 3. The structure of the all-in-one machine.

The machine was designed as follows:

(1) In order to integrate transplanting and sorting operations and reduce workflow, based on the existing RGB-D camera side-view detection scheme, we propose dynamic detection of seedlings during their transportation after pick up from the tray holes. This achieves integrated and rapid detection of ungerminated, small, weak, and damaged seedlings during the transplanting process, ensuring the integrated operation of sorting and transplanting.

(2) In order to reduce the size of the all-in-one machine, this study considers combining the seedling delivery lines for transplanting and replanting into one. The innovative strategy of transplanting and replanting seedlings from the same tray ensures seedling supply, so as to realize the integration of the two modules. In turn, the flat and lightweight multi-claw transplanting and linear-SCARA single-claw combined replanting mechanism is optimally designed to effectively reduce the space of two modules.

(3) The structure configuration and seedling sequence planning of each operation module are carried out to build a multi-functional integrated layout scheme for transplanting, seedling detection, discarding, and replanting. We propose a cooperative control system for the master operation (sorting–transplanting) and slave operation (replanting), so as to realize the high-speed transplanting operation of the all-in-one machine. On the basis of not changing the structure and operation route of the existing transplanting equipment, we integrate the inspection and replanting functions into the transplanting operation to achieve multi-functional integration. In addition, the operation efficiency meets the actual production requirements.

This all-in-one machine can provide high-performance automatic transplanting equipment for factory seedlings and can provide solution support for automatic transplanting of various seedlings in greenhouses and on dry land, which is of great practical significance to promote the rapid development of factory seedlings and, in turn, the horticulture industry in China.

2.3. Key Systematic Design Method

2.3.1. Dynamic Detection of Seedling Transport

The existing intelligent detection system is mainly oriented toward the detection of ungerminated and small seedlings in the tray before/after transplanting or replanting. The overlapping leaves of the tray seedlings are severely obscured, making it extremely difficult to accurately measure the parameters of the seedlings [40,41]. From the camera detection perspective, there are two main positions for cameras relative to the tray for seedling quality detection, as shown in Figure 4. In one configuration, the camera is above the seedlings and looks down vertically into the tray for identification; however, only leaf information can be detected. The other configuration is when the camera is at the side of the tray and can detect information about the leaves and stalks of the seedlings. However, in transplanting operations, the seedling picking claw can cause damage to the seedling lump, and existing detection methods cannot provide effective feedback.

Figure 4. Existing seedling quality detection methods.

As can be seen in Figure 5, this paper considers detection when the tray seedlings are clamped out of the holes and at a certain height above the tray; the tray seedlings are in a suspended state, and the seedling lump is not covered by the tray. At the same time, there is a certain spacing between adjacent seedlings, which solves the problem of leaf shading. The camera can detect a variety of information about the leaves, stalks, and lumps of the tray seedlings. However, in the new detection scheme, the image background is complex, and the detection objects—leaves, stalks, and seedling lumps—are no longer applicable to ordinary CCD cameras. The RGB-D camera can obtain the object depth and color information synchronously, which can split the background and seedlings more accurately and does not need to be equipped with a light box. So, we propose a super-close-up side view detection method for tray seedlings based on an RGB-D camera. In order to find the best detection position, the height of the camera is adjusted using a lift rod, and the horizontal distance between the camera and the seedling is adjusted using a guide rail and slider.

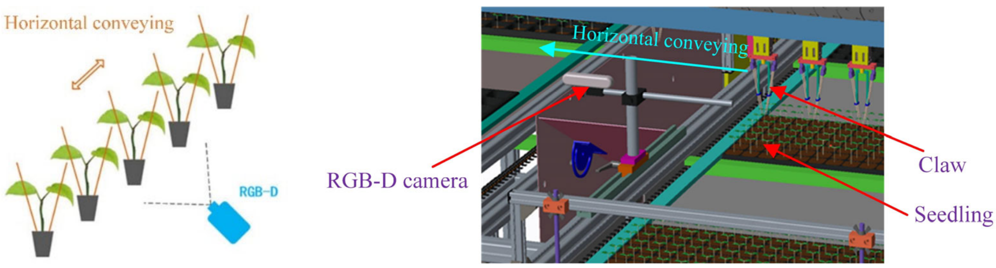


Figure 5. Dynamic detection of seedlings during transport.

As can be seen in Figure 6, the tray seedlings pass through the pick-up area, detection area, discarding area, and planting area in sequence during the transplanting process. Without changing the existing movement and flow of the transplanting operation, the seedlings are sorted (detection and discarding) without stopping on the way to the transplant, thus making the transplanting and sorting an integrated operation.

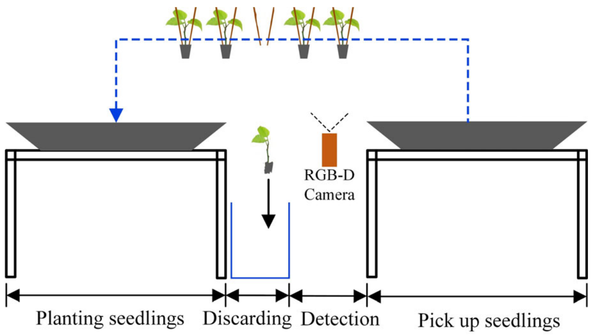


Figure 6. Transplanting–sorting integration operation.

2.3.2. Seedling Transplant–Replant from Same Tray

Based on the integrated sorting–transplanting layout scheme, we further consider the integration of transplanting and replanting operation modules. In practice, the specifications of the transplanting and replanting trays and conveyor lines are the same. In order to reduce the number of tray delivery lines and simplify the tray delivery process, we integrate the seedling sources for transplanting and replanting into one tray. The seedlings in one area of the tray are used as the source of transplants, and the other areas are used as the source of replants.

As shown in Figure 7, the first row of seedlings in the tray is used as a source of replanting seedlings, and the remaining rows of seedlings are used as a source of transplants. The system effectively integrates the tray and delivery module for transplanting and replanting and thus also integrates the transplanting and replanting operations.

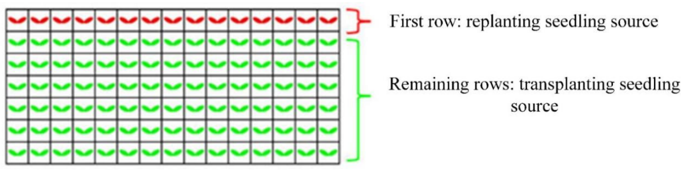


Figure 7. Transplanting–replanting within the same tray for pick-up seedlings.

Only four functional modules are used in this all-in-one machine: a tray delivery module, detection module, transplanting module, and replanting module. As shown in Figure 8, we reduce the tray conveying line from four to two, and thus the complex system and operating space problems of the existing system are solved.

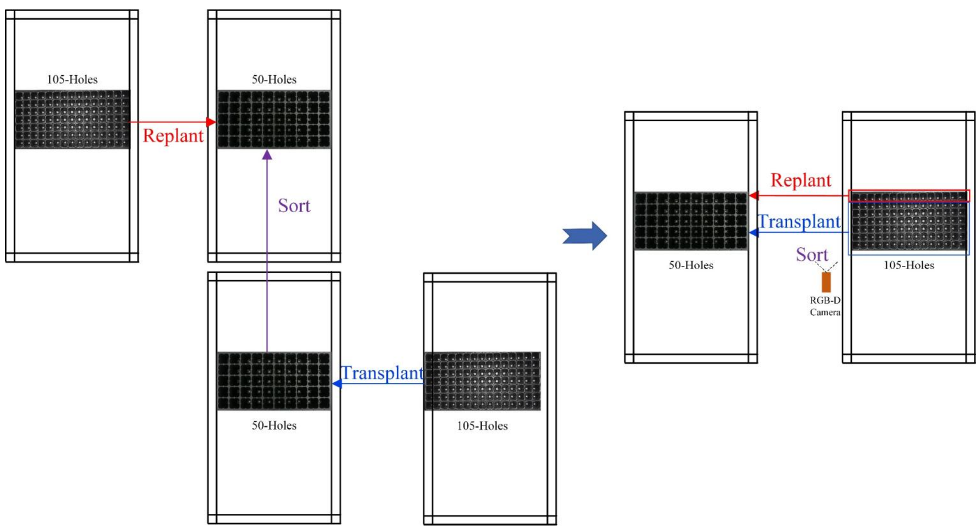


Figure 8. Integrated tray conveying line.

Thus, this paper focuses on the flat and lightweight design of the multi-claw transplanting and single-claw replanting mechanism, which can achieve the high-speed transplanting of multi-claw rows while minimizing the interference space of the replanting mechanism.

2.4. Key Mechanism Design

2.4.1. Multi-Claw Transplanting Mechanism

The transplanting mechanism needs to complete the actions of picking up, transporting, and planting, which directly determine the quality and efficiency of transplanting. In order to improve operational efficiency, the transplanting mechanism is equipped with multiple claws. The existing multi-claw transplanting mechanism usually uses servo motors to adjust the distance between the claws to adapt to different sizes of trays. The multi-claw transplanting mechanism in Figure 9 is complex and large in size and weight, resulting in complicated transplanting operation movements and greatly limited transplanting efficiency and performance [42]. With this transplanting mechanism, the width far exceeds the transplanting seedling source area and occupies the operating space of the replanting mechanism, resulting in the inability to perform replanting operations.

Figure 9. Existing multi-claw transplanting mechanism.

The transplanting mechanism directly determines the quality and efficiency of transplanting. The requirements of this study are: simple structure, fast reciprocating motion, small size, short path, and reduced interference space with the replanting mechanism. In the measurements of the tray parameters, we found a proportional relationship between the adjacent hole spacing of the high-density tray and the low-density tray. The center distance between adjacent holes is 34 mm for the high-density tray and 51 mm for the low-density tray, as shown in Figure 10 [37]. The distance between the centers of the three adjacent holes in the high-density tray is equal to the distance between the centers of the two holes in the low-density tray. Therefore, the multi-claw transplanting mechanism in this paper is designed with five picking claws; three rounds are needed to pick up a full row in high-density trays and two rounds to plant a full row in low-density trays. We use the Chinese standard tray specifications, avoiding the use of the existing complex and large transplanting mechanism, making the multi-claw transplanting simple in structure, light in quality, and high in efficiency.

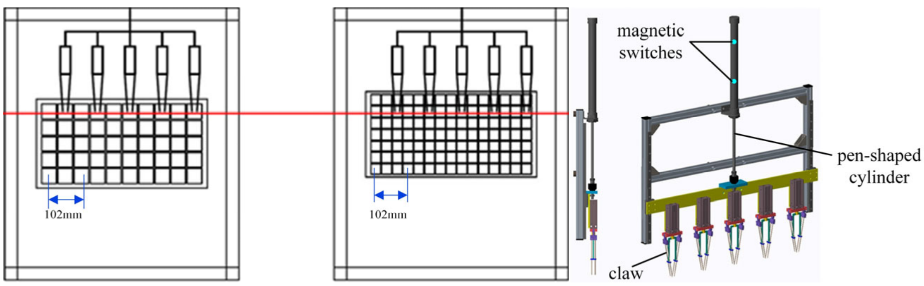


Figure 10. The flat multi-claw transplanting mechanism.

The synchronous lifting and lowering of the five claws are controlled by the pen-shaped cylinder, and the opening and closing of the five claws are controlled by independent micro cylinders. The pen-shaped cylinder is fitted with two magnetic switches for precise control of the claw movement to the specified height. At the same time, the number of claws can be flexibly configured to suit different sizes of trays. In transplanting operations, the multi-claw transplanting mechanism is required to reciprocate between high-density trays and low-density trays. The transplanting path is shown in Figure 11, where A is the pickup location, B~C is the transport path, and D is the planting location. This transplanting operation path is short, simple, and reliable to control. Due to the light weight of the multi-claw transplanting mechanism, horizontal conveying can be performed by only a single linear servo module. There are five photoelectric sensors installed on the left and right of the conveyor belt to control the precise movement of the transplanting mechanism to the corresponding seedling picking and planting positions.

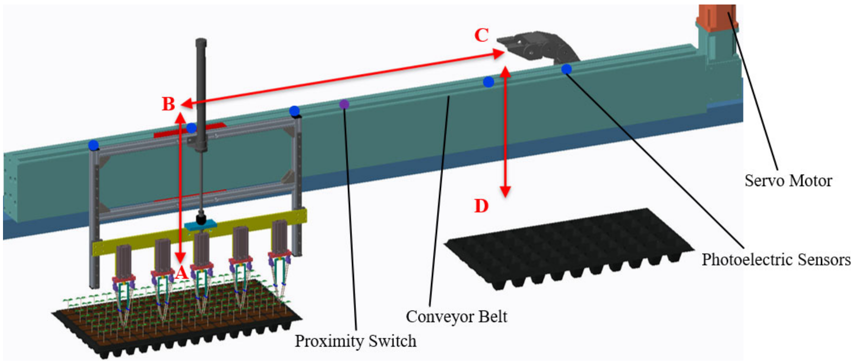


Figure 11. Transplanting path.

2.4.2. Single-Claw Replanting Mechanism

The replanting mechanism needs to quickly and precisely plant the tray seedlings into the empty holes, and the action needs to be fast and flexible to reduce interference with the multi-claw transplanting mechanism. During operation, both sides of the tray move intermittently, and the position of the picking and planting area is constantly changing; thus, the replanting mechanism needs to adapt to the variability of the target position. In this paper, industrial robots are considered to perform replanting operations. The six-axis robot arm movements and paths are too complex for collaborative work with transplanting mechanisms. At the same time, the control method of the six-axis robot arm is more computationally intensive than the four-axis arm, leading to an increase in the number of controller operations [43]. The design requirements of the replanting mechanism are fast reciprocating movement, small space occupation, and flexible movement. The four-axis SCARA robot is the most suitable robot for this study because of its small size, simple transmission, reliable performance, and ability to quickly and flexibly complete the pick-and-place motion in a narrow space.

To achieve a complete replanting operation, the SCARA needs to cover the center of the rightmost hole in the first row of high-density trays, and the center of the leftmost hole in the first row of low-density trays. As shown in Figure 12, the SCARA is installed on top of the linear module, that is, a walking axis is added to the SCARA, and the working space of SCARA is extended by the linear module. The SCARA can be used for transplanting between O_1 and O_1' points at high speed, picking up seedlings at O_1 and planting them at O_1'; thus, the working radius of SCARA can be greatly reduced, and replanting can be done with a smaller and lighter SCARA. Meanwhile, proximity switches are installed at O_1 and O_1' points to ensure precise positioning movement of SCARA between O_1 and O_1'.

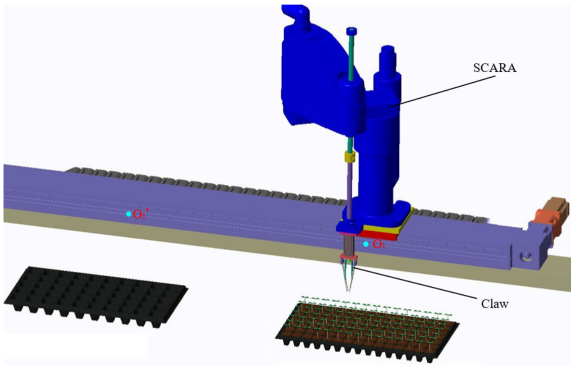


Figure 12. 3D view of replanting mechanism.

To achieve full coverage and high-speed operation with the SCARA robot for replanting pick-up and planting operation range, the minimum working radius of the SCARA should be calculated to provide the parameter basis for SCARA selection. As shown in Figure 13, the distance between the center of the leftmost hole in the first row E and O_1' in the low-density cavity tray is the minimum working radius, R, of the SCARA when the replanted seedling source reaches the limit position.

$$R = \sqrt{ED^2 + (O_1A + AB)^2}; AB = 6.5\Delta_1 \quad (1)$$

Here, ED is the distance from the center of the first hole in the first row of the low-density cavity tray to the line of symmetry of the tray, ED = 229.5 mm. Δ_1 is the center distance between adjacent holes along the width of the high-density tray, Δ_1 = 36.5 mm. O_1A is the width of the linear module, O_1A = 90 mm. The minimum working radius R of SCARA is 399.7 mm as calculated by the formula. The working radius of SCARA in the market is 450 mm and 500 mm; combined with the center distance of the cavity hole of the high-density tray and low-density tray, the working radius of SCARA needs to leave a certain margin when selecting the model, so 500 mm was chosen. Then, considering the parameters of weight, volume, upper and lower axis travel, and height, IAI's IX-NSN5016 high-speed SCARA was finally selected.

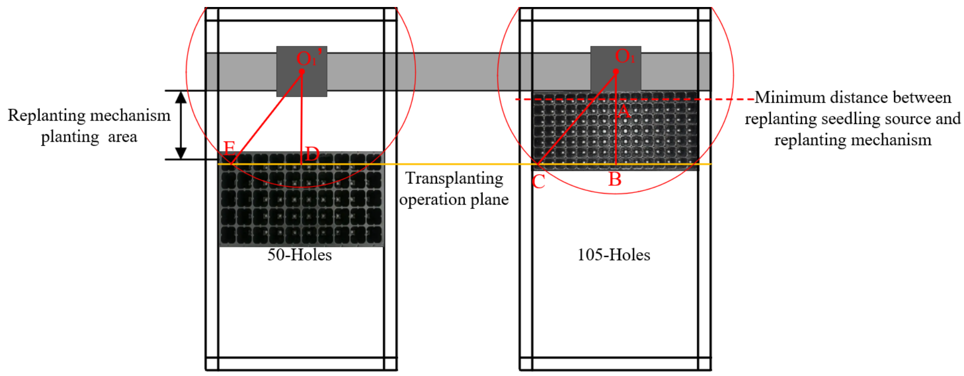


Figure 13. SCARA minimum working radius.

The SCARA has three rotating joints and one translating joint, where the rotating joints control the plane movement of the robot arm, and the moving joints control the lifting movement of the claw. In this paper, the kinematic matrix equations are established by combining the SCARA parameters, and the workspace analysis of the SCARA robot is carried out by MATLAB; its simulation cloud is shown in Figure 14. Based on the simulation results, the SCARA operation radius meets the target requirement of 500 mm. It was further confirmed that the selected SCARA meets the needs of replanting operations.

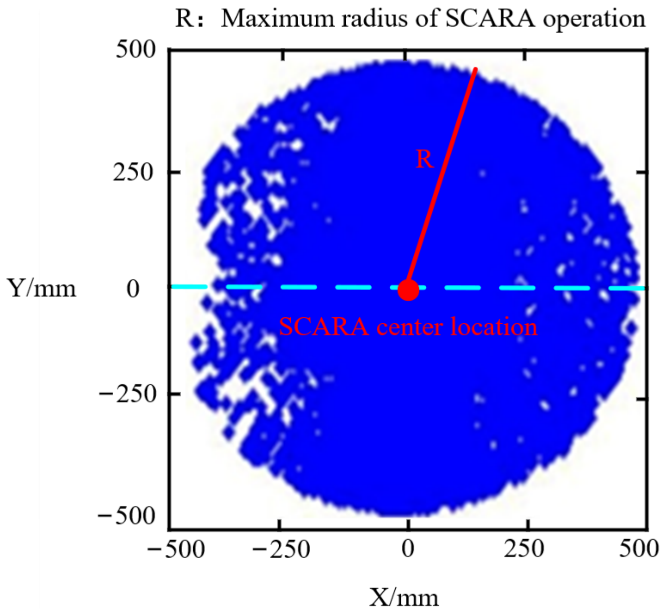


Figure 14. SCARA workspace curve.

3. Control Strategy Design

3.1. Seedling Sequence for Transplanting–Replanting

A good seedling rate of a factory nursery is 90~95%, so the probability of ungerminated, small, and weak seedlings is 5~10%. The maximum number of non-healthy seedlings present in a 105-hole high-density tray is 5.25~10.5, while a single high-density tray requires two low-density trays to complete the planting. Therefore, a single high-density tray needs to be left with 10 seedlings for replanting.

In transplanting operations, the location of the low-density trays where the replanting holes occur is random. Since the operation technology of high-speed transplanting equipment is relatively mature, this paper refers to the operation path of existing equipment for the seedling sequence of a multi-claw transplanting operation. In the high-density tray, each row is picked from left to right, and in the low-density tray, each row is planted from left to right. In order to avoid interference and collision between the replanting and transplanting mechanisms, the seedling sequence for replanting operations is as follows: the replanting source is taken in order from right to left, and low-density trays are planted from left to right (Figure 15).

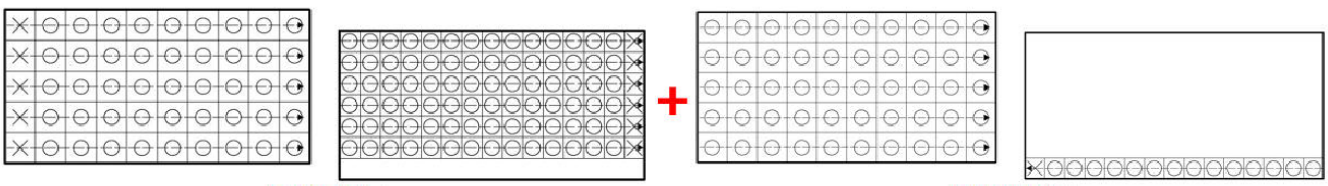
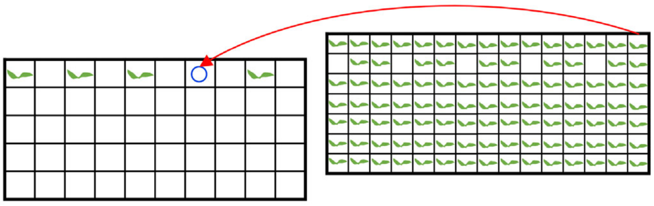


Figure 15. Scheme of transplanting and replanting seedling sequence.

For the integrated transplanting–replanting operation seedling sequence, three methods are considered in this paper. (1) The resulting empty holes were replanted immediately after each completed transplanting (Figure 16a). (2) After each completed row of transplants in low-density trays, the resulting empty holes were replanted (Figure 16b). (3) The low-density trays were replanted after multi-row transplant was completed, and the resulting empty holes were replanted (Figure 16c).



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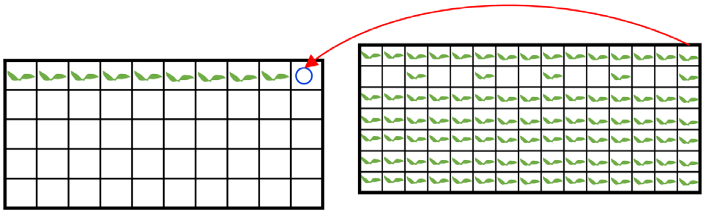
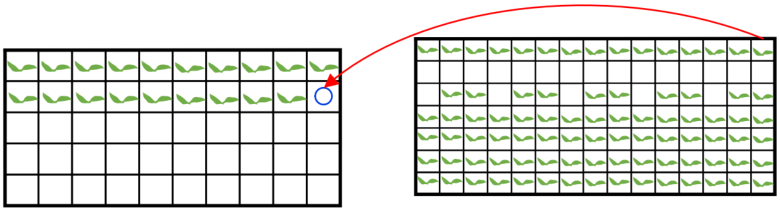


(**b**)



(**c**)

Figure 16. Seedling sequence for transplanting–replanting integrated operation.

Based on the principle of simultaneous operation of transplanting and replanting, it is obvious that option 1 is the most reasonable choice. However, this method requires a very high replanting speed, within 6 s for a single plant, and needs to avoid the transplanting mechanism in actual operation. Thus, this method needs to be optimized. When there are more empty holes in transplanting, the replanting mechanism replants one hole at each subsequent transplanting operation, and so on, until all empty holes are replanted (Figure 17). If all transplanting is completed for a single high-density tray and replanting is not completed, the transplanting mechanism stops until all empty holes are replanted and then activates transplanting for the next low-density tray.

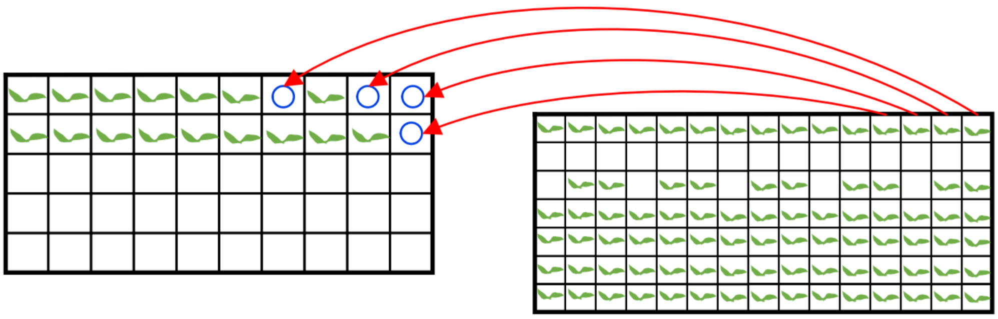


Figure 17. Optimum method of integrated seedling sequence.

3.2. Synergistic Control of Sort–Transplant–Replant

For the integrated transplanting–sorting operation, the single operation cycle consists of five steps: multi-claw seedling picking, horizontal transfer, seedling quality detection, non-healthy seedling discard, and multi-claw seedling planting. After finishing the seedling picking operation, the linear module drives the multi-claw transplanting mechanism to the low-density tray at a fixed speed V (V = 1.5 m/s) with uniform motion. When passing through the detection area, the multi-claw transplanting mechanism touches the proximity switch to activate the RGB-D camera for the first seedling image acquisition. Image acquisition of the remaining four seedlings is controlled by a timer and taken once at a fixed time interval *t*. The RGB-D camera is placed in standby mode after completing five shots and waits for the next trigger round.

$$t = \frac{S}{V} \tag{2}$$

Here, *S* is the distance between the centers of adjacent claws, and *V* is the speed of the multi-claw transplanting mechanism to the low-density tray. The depth and color information acquired by RGB-D synchronization is first used to achieve reliable rejection of background information based on a fixed depth threshold and seedling color feature information. Then, the leaf, stalk, and lump areas are segmented by swelling erosion and contour extraction and use the minimum outer rectangle for region-1 and region-2 to obtain the height and width of the seedling. Finally, pixels are extracted for region-3 to calculate the lump area, and skeleton extraction and vertical corner point fitting are performed for region-2 to obtain the stalk uprightness information; the detection results are shown in Figure 18.

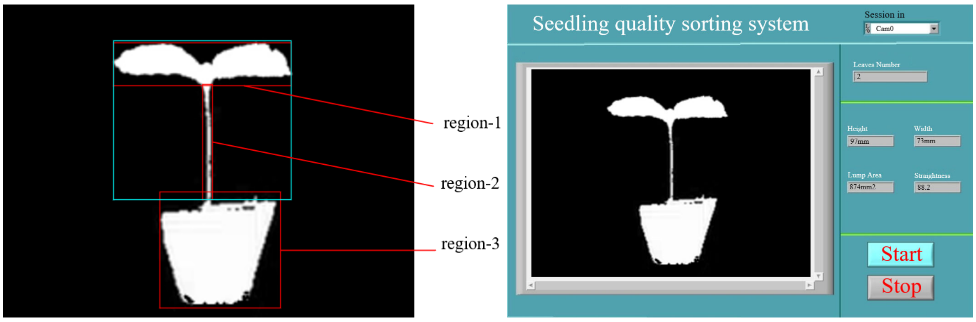


Figure 18. Multi-indicator detection system for seedlings.

The detected physical dimensional parameters are compared with the threshold interval set by the detection system, and those that fail are treated as non-healthy seedlings. Based on the detected results, the solenoid valve of the corresponding serial number is controlled to remove non-healthy seedlings in the discard area. This method can be used to detect and discard seedlings without stopping during the seedling transport.

High-speed automatic operation requires the synergy of transplanting and replanting operation modules. The single replanting operation cycle consists of four parts: seedling picking (B″→B′), robotic arm avoidance (B′→B″), horizontal transfer (O_1→O_1′), and seedling planting (C″→C′). As shown in Figure 19, the synergistic control of transplanting–replanting require the following: (1) The replanting mechanism pick-up and the return of the robot arm to the *B*″ position must be done after the transplanting mechanism has left the high-density tray pick-up area. (2) The planting of the replanting mechanism and the return of the robot arm to the *C*″ position must be done after the transplanting mechanism has left the low-density tray planting area.

3.3. Control System and Operation Process

The operation of the all-in-one machine has many steps and processes and requires high precision of movement for each module. It requires effective control of both sides of the tray conveying line, multi-claw transplanting mechanism, single-claw replanting mechanism, and detection module. At the same time, real-time communication is required between each functional module, and signal acquisition and feedback are required for multiple servo motors, solenoid valves, and various sensors, resulting in a highly complex process. As shown in Figure 20, PLC is selected as the main controller, and the detection module detects the seedling quality through the IPC and sends the unhealthy seedling information to PLC through RS485. The PLC sends the empty hole coordinate information to the replanting module via RS232. The modular control system in this paper allows each functional block to moves synchronously according to a set sub-module program.

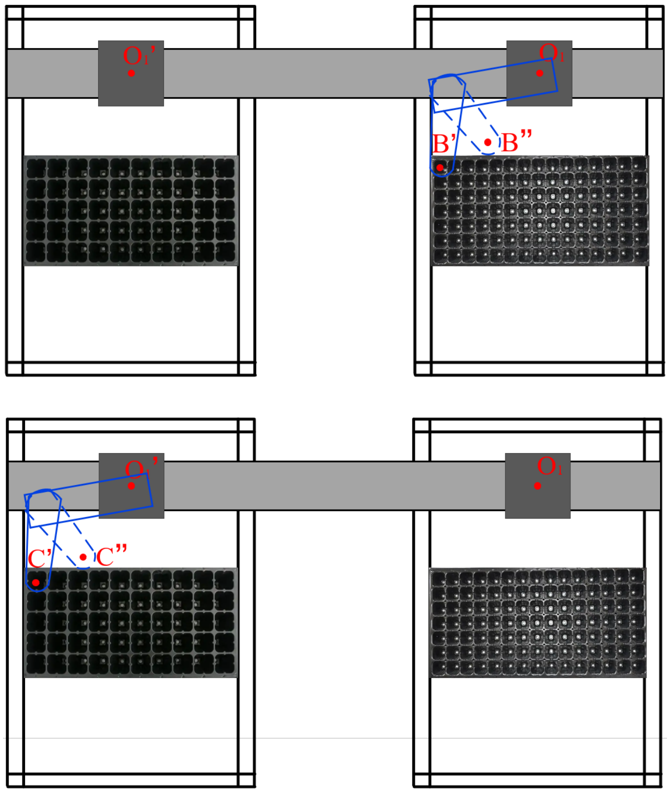


Figure 19. Diagram of replanting mechanism operation.

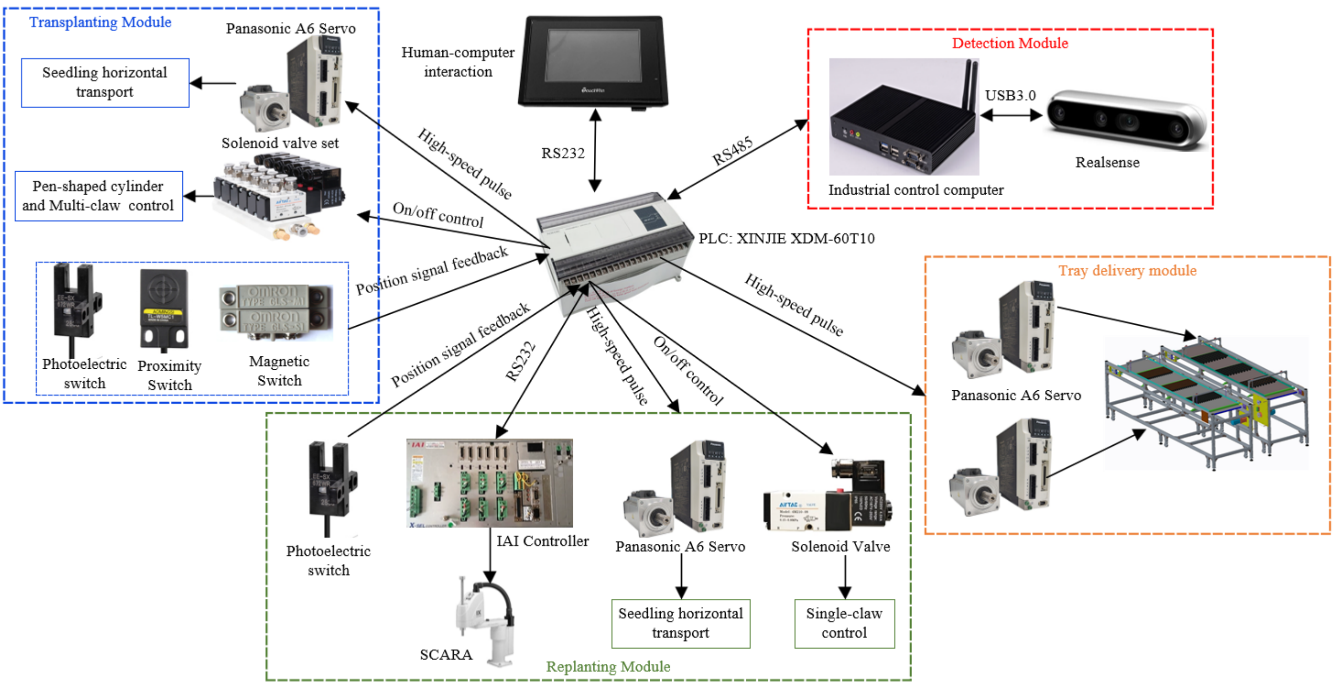


Figure 20. Control system.

By studying the sorting–transplanting–replanting cooperative control system, the operation flow of the whole machine was further optimized, and the detailed operation flow in Figure 21 was obtained.

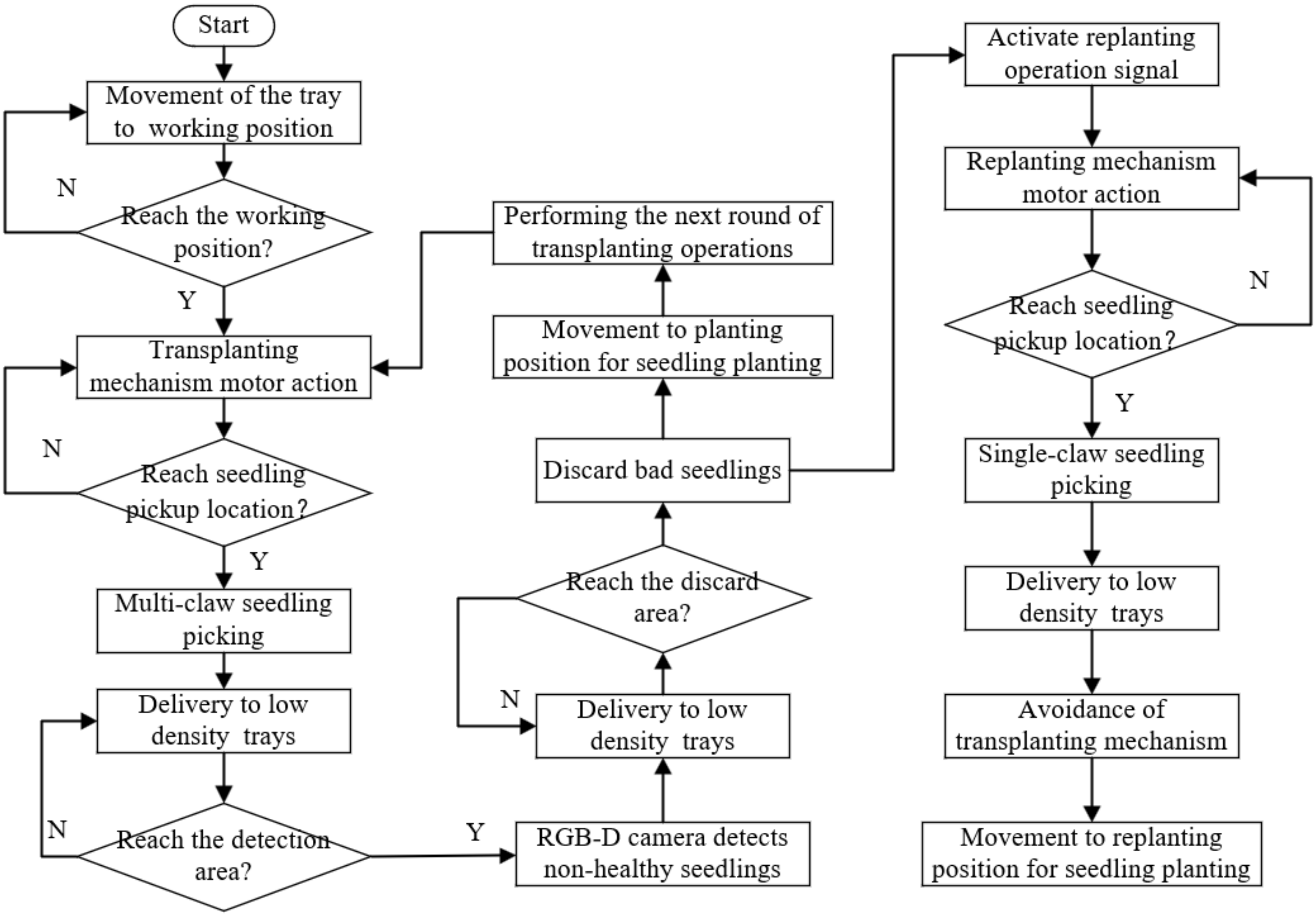


Figure 21. Detailed work flow.

4. Results and Discussion

4.1. Experimental Method

According to the design plan of the all-in-one machine, our team independently completed the processing, assembling, and commissioning of the all-in-one machine at the Key Laboratory of Modern Agricultural Equipment and Technology of Ministry of Education, Jiangsu University (Figure 22). The volume of the whole machine is $2.93 \times 2.76 \times 2.06$ m, the power is 5 kw, and the weight is 900 kg.

In this paper, the cucumber seeds of Jingyou NO.1 were selected for cultivation, and the substrate was composed of grass charcoal, vermiculite, and perlite in the ratio of 3:2:1. The temperature of the cavity tray seedlings was reduced, and watering was controlled 3 days before the trial. The average moisture content of the seedling lump was between 55% and 60%, determined by randomly measuring 10 holes per tray using a pin-type moisture tester. The entire process was recorded by an HD video camera (SONY HDR-XR100E). The speed of transplanting and replanting operations of the machine was recorded separately using multiple stopwatches.

Figure 22. All-in-one machine.

The number of non-healthy seedlings in all trays was manually counted and recorded before the experiment for subsequent statistics on replanting performance. Setting the all-in-one machine to 900, 1000, and 1100 transplant cycles/hour, three sets of integrated operational trials were conducted for each transplanting cycle according to the seedling sequence of transplanting–replanting. The main indicators to measure the performance of the prototype are transplanting success rate η_1, replanting success rate η_2, good seedling rate before replanting η_3, and good seedling rate after replanting η_4.

$$\eta_1 = \frac{N - (a+b) - (c+d)}{N - (a+b)} \tag{3}$$

$$\eta_2 = \frac{e}{(a+b) + (c+d)} \tag{4}$$

$$\eta_3 = \frac{N - (a+b) - (c+d)}{N} \tag{5}$$

$$\eta_4 = \frac{N - (a+b+c+d-e)}{N} \tag{6}$$

Here, N is the total number of transplants, a is the number of ungerminated seedlings, b is the number of small and weak seedlings, c is the number of failed picking by the claw, d is the number of damaged seedlings caused by the claw, and e is the number of successful replants.

According to the above experimental methods, the test process of real-time recording, and statistical data, Equations (3)–(6) were used to calculate the experimental results.

4.2. Results

The above method and steps for continuous integrated operation experiments are shown in Figure 23.

(**a**) (**b**)

Figure 23. *Cont.*

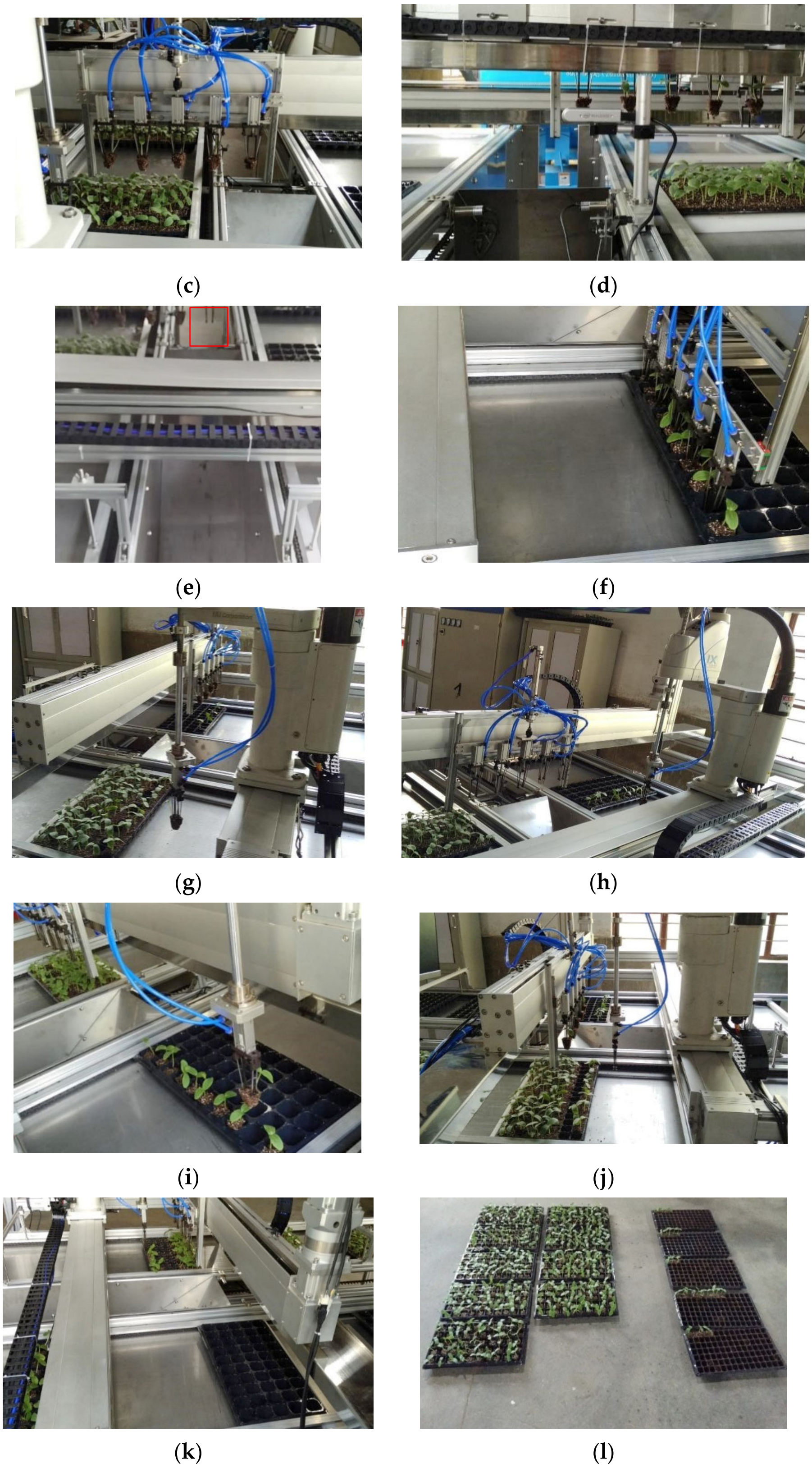


Figure 23. Integrated sorting–transplanting–replanting operation. (**a**) Two side tray feeds. (**b**) Seedling pickup by transplanting mechanism. (**c**) Horizontal conveying. (**d**) Seedling quality detection. (**e**) Discarded seedlings. (**f**) Planting seedlings. (**g**) Replanting mechanism picks up seedling. (**h**) Transplanting mechanism reset. (**i**) Replanting empty holes. (**j**) Tray advances one row. (**k**) Transplanting new trays. (**l**) Final operation effect.

During the operation, the relevant data are recorded in real time, and the operation effect is calculated.

From Tables 2–4, the average transplanting success rate (η_1) showed a decreasing trend with increasing transplanting efficiency at different numbers of transplanting cycles per hour. At 1000 transplanting cycles per hour, η_1 was as high as 97.1%, while increasing to 1100 transplanting cycles per hour resulted in a decrease of η_1 to 94.39%. It was concluded that an increase of transplanting speed would lead to an increase of picking failure rate, so the best transplanting cycle was determined to be 1000 times/h, which also further verified the working performance of the transplanting system.

Table 2. Results of 900 transplanting cycles/h.

Number/ Indicator	N	a	b	c	d	e	η_1(%)	η_2(%)	η_3(%)	η_4(%)
1	50	1	4	1	0	6	97.78	100	88	100
2	50	0	2	0	2	4	95.83	100	92	100
3	50	2	2	1	2	6	93.48	85.71	86	98
Average	50	1	2.67	0.67	1.33	5.33	95.7	95.24	88.67	99.33

Table 3. Results of 1000 transplanting cycles/h.

Number/ Indicator	N	a	b	c	d	e	η_1(%)	η_2(%)	η_3(%)	η_4(%)
1	50	1	2	0	0	3	100	100	94	100
2	50	2	2	1	1	5	95.65	83.33	88	98
3	50	1	3	0	2	5	95.65	100	88	100
Average	50	1.33	2.33	0.33	1	4.33	97.1	94.44	90	99.33

Table 4. Results of 1100 transplanting cycles/h.

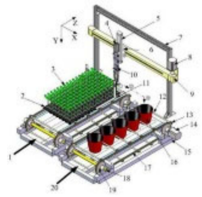
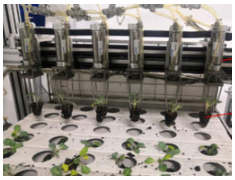
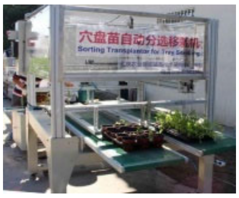
Number/ Indicator	N	a	b	c	d	e	η_1(%)	η_2(%)	η_3(%)	η_4(%)
1	50	0	1	1	1	3	95.92	100	94	100
2	50	2	1	1	2	4	93.62	66.67	88	96
3	50	0	3	2	1	4	93.62	83.33	88	96
Average	50	0.67	1.67	1.33	1.33	3.67	94.39	83.33	90	97.33

The average replanting success rate (η_2) showed a decreasing trend with increasing transplanting efficiency. When the number of transplants per hour was increased from 1000 to 1100, η_2 decreased by 11.11%. This is mainly due to the decrease in the success rate of seedling retrieval leading to an increase in the number of replanted empty holes, which ultimately caused a significant decrease in η_2. At the same time, the data change of good seedling rate before and after replanting (η_3 and η_4) showed a significant increase in good seedling rate after replanting (η_4). This further verifies the working performance of the replanting mechanism.

The above analysis shows that the all-in-one machine designed in this paper has reliable performance, and the seedling sequence for transplanting–replanting and master–slave cooperative control strategy are reasonable and effective. The best integrated operation was achieved at a transplanting cycle of 1000 times/h, corresponding to a transplanting efficiency of 5000 plants/h, which is consistent with the designed transplanting efficiency.

In order to verify the advantages of the all-in-one machine, the research results of several Chinese scholars were selected for comparison. As can be seen in Table 5, our machine is the best in terms of operational efficiency and transplanting success rate. Meanwhile, in terms of functional modules, our machine has multi-functional transplanting, sorting, and replanting, while other machines operate with a single function.

Table 5. Comparison with other studies.

Author	Machine	Efficiency (Plants/Hour)	Success Rate (%)	Function
Kang et al. [11]		2000	99	Transplanting
Han [38]		1200	93.87	Transplanting
Wang [44]		900	90.23	Transplanting
Tong et al. [45]		3956	96.7	Transplanting
Feng et al. [22]		700	90	Transplanting and Sorting
Our machine		5000	99.33	Transplanting, Sorting, and Replanting

5. Conclusions and Future Works

This paper summarizes the shortcomings of existing equipment, addresses the specific agricultural development needs of China, and finally designs an intelligent multi-functional seedling transplanting system. We successfully integrated the functions of sorting, transplanting, and replanting into a single machine. In the development process, we propose the key innovative strategies of seedling dynamic detection during transplanting and transplanting–replanting within the same tray. Then, through the flat design of the transplanting–replanting mechanism and the establishment of a multi-module co-operative control strategy, stable and reliable multi-functional synchronous operation is realized. Finally, as determined by performance testing of the transplanting operation of cucumber seedlings, the operation efficiency of the machine is 5000 plants/h, and the good seedling rate after replanting is 99.33%. The development of this machine can provide equipment support for factory nurseries and technical reference for other scholars' research and development work, which is of great significance.

Due to practical conditions, no experiments on the transplanting of tray seedlings of other crops were conducted. In future research work, we will conduct transplanting experiments with seedlings of peppers, tomatoes, and eggplants. Based on the results of the experiments, the operating path and speed of the machine will be optimized. We will also promote the machine for demonstration in several factory nurseries in conjunction with the national agricultural policy.

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