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Design and test of an efficient seedling pick-up device with a combination of air jet ejection and mechanical action

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Abstract

Low degree of transplanting automation will affect production efficiency and planting quality in vegetable cultivation. A new seedling pick-up device was designed and constructed to reduce direct grasping damages to seedlings and improve transplanting efficiency. The pick-up device consists of an air jet loosening device, a flexible pick-up manipulator, a parallel feeding device, and a multi-axis motion control system. Its working principle is to use air jet ejection to assist in loosening of seedling roots from the tray cells, grasp their stems for extracting with the pick-up manipulator, and finally transfer them to the delivery device for feeding into the planting device as needed. The mechanical structure and working parameters of each component were designed, and the control system was constructed according to the working requirements of ejecting, extracting, transferring, and discharging operations. A prototype of the new pick-up device was constructed, and its performance evaluation was conducted using an orthogonal experimental design using cucumber, pepper and caluiflower as test objects. The results showed that the test object, the root lump's moisture content and the loosening way (either as a whole or individual loosening of seedlings) had significant effects on the success ratio in picking up seedlings. Overall, the success in picking up seedlings from the cell was found to be influenced by horticultural and mechanical factors. Under the optimal level group, the maximum success ratio for automatic picking up seedlings was up to 94.49% for pepper while that of cucumber and cauliflower recorded 90.75% and 92.62%, respectively. The seedling pick-up performance was satisfactory for efficient transplanting requirements.

Introduction

The majority of conventionally grown vegetables, such as cucumber (*Cucumis sativus L.*), tomato (*Lycopersicon esculentum Mill.*), pepper (*Capsicum annuum L.*), cabbage (*Brassica oleracea L.*) and so on, are suitable for transplant production, whether they are cultivated in the open field or in the greenhouses (Prasanna *et al*., 2008; Lim *et al*., 2017; Ma *et al*., 2020; Han *et al*., 2022). Especially for those solanaceous and leafy vegetables, transplant production has become a beneficial and specialized procedure for their industrialization development (Mao *et al*., 2014; Khadatkar *et al*., 2018; Han *et al*., 2019). Since the seedlings grown in plug trays are in an orderly array that might be easily handled, they are widely used in actual production (Ting *et al*., 1992;

Prasanna *et al*., 2008; Mao *et al*., 2014).

Currently, China is the largest producer and consumer of vegetables in the world, with a production of 21.87 million hectares and a yield of 767.11 million metric tons in 2021. According to the statistics, China produces up to 350 billion plants of professional plug seedlings annually (Sun *et al*., 2021). However, seedling transplanting as a well-defined repetitive task is still technologically backward. The main planting method in small field production is manual transplanting of vegetable seedlings, which is a laborious and time-consuming field operation (Ting *et al*., 1992; Tsuga 2000; Parish, 2005; Prasanna *et al*., 2011; Mao *et al*., 2014). This traditional practice is to separate seedlings by one hand and press down the roots in the soil with another bare hand into prepared furrows or holes (Khadatkar *et al*., 2018). A step further away from the traditional manual transplanting has that relatively large-scale vegetable production is currently experimenting with the usage of semi-automatic seedling transplanting machinery. It requires manually feeding seedlings one by one for the cup-type or finger-type planting mechanism in a limited operating speed, which is not suitable for continuous operation over a long period (Tsuga 2000). Labour shortage and efficient rotation of cropping production have made vegetable growers become increasingly interested in automating transplanting operations (Han *et al*., 2019).

Research on ensuring precision in automatic transplanters and their components began several years ago. Based on the advanced industrial technology, some robotic devices have been used to examine the workability and productivity of seedling automatic transplanting (Kutz *et al*., 1987; Ting *et al*., 1992; Ryu *et al*., 2001). A robotic manipulator with 5 degree of freedom and a gripper was mounted on a commercial pot-type mechanical transplanter, which had been modified to match the manipulator's pick-place operation (Hwang *et al*., 1986). The computer graphics and simulation were used to study robotic transplanting feasibility of bedding plants, followed by validation and testing with a Puma 560 robot (Kutz *et al*., 1987). Despite in inefficiency to transplant one 36-cell growing flat at 3.3 min, the corresponding research demonstrates that the robot could transplant most of the seedlings with little damage to their plants. Subsequently, a five-bar type seedling pick-up device for vegetable transplanters was designed and tested to assess its maximum extracting performance (Choi *et al*., 2002). The pick-up device could extract seedlings from a 200-cell tray of seedlings and transfer them to a point where they would be set into the soil. Extraction failures occurred with younger seedlings whose root soils were not well developed. With the development of high-speed transplanting technology, a whole row of seedling pick-up transplanter was developed to promote the mechanization of vegetable transplanting work (Kang *et al*., 2017). The experimental results in fork-type picking of 200 seedlings were that the missing plant ratio was 4% with 6 of the seedlings dropping during transfer. Insufficient flexible automation leads to unstable operation quality, which makes working efficiency not be fully exerted.

In view of the technological advancement of seedling transplanting, several researchers in China have also focused on the design of automatic pick-up mechanisms and their structure parameter optimization (Cui *et al*., 2013; Ni *et al*., 2015; He *et al*., 2016; Jin *et al*., 2018; Han *et al*., 2018). Through the kinematic analysis, a novel kind of rotary seedling pick-up mechanism of planetary gear train was proposed and established with combined type gears of incomplete denatured eccentric-circular and non-circular gears. The computer-aided analysis and optimization software with human-computer interaction method was developed to realize parameters optimization of the seedling pick-up mechanism. Laboratory tests showed that the mechanism had the success ratio of seedling pick-up 96.3% without interference during seedling transporting when the rotation speed of the mechanism was 50 r/min. However, there would be a certain failure to pick up seedlings. A mechanically-driven system with automatic picking and throwing for plug seedling was developed by combining the latest transplanting mode of plug seedlings and agronomic requirements in Xinjiang Region, China (Zhang *et al*., 2021). There would be some fluctuations for the overall success rate of seedling transplantation in the speed range of 64-88 plants/min. The corresponding seedling grippers had been also studied according to the characteristics of the transplanted objects. The existing design concepts range from the simple grippers to the custom end-effectors (Sun *et al*., 2010; Han *et al*., 2015; Tian *et al*., 2022). Despite some of these attempts, automated transplanting has not seen much success and popularization in the field production. Consequently, the fully automatic transplanters for plug seedlings are not widely used by vegetable growers. They are often seen being showcased at the product exhibition or the field demonstration of new machinery.

The successful integration of an automatic machine with seedling transplanting requires an operational pick-up device. The goal of this study was to design an efficient pick-up device for automatic transplanting of vegetable seedlings with a combination of mechanical, electrical and pneumatic techniques. Its performance was evaluated under actual production conditions. This research provides several innovative ideas for the development of automatic and efficient transplanting machinery.

Materials and Methods

Plug seedlings for transplanting

Transplant production of vegetable seedlings is carried out according to the agricultural professional standard of China (NY/T 2119-2012, 2012). A 128-cell soft injection molded polystyrene plastic trays are widely used with the arrangement of 8×16 cells and the overall dimension of 540 mm length × 280 mm width. The shape of the cell is an inverted truncated pyramid, and its cell dimension is 42 mm height × 32 mm top × 10 mm bottom. The seedling substrate was a mixture of herbaceous peat, perlite, vermiculite, and other agricultural materials in a standard volume proportions. Seeds were sown per cell containing 22 mL of substrates and then covered with about 2 mm of fine vermiculites. The sown plug trays were placed in the seedling beds maintained at 26 ± 2 °C for germination. Seedling growth temperatures were recorded to be 24 ± 2 °C in the day and 16 ± 2 °C at night, respectively, with 65% to 75% relative humidity variations. Finally, those plug seedlings are produced with some day growth and the following 4 days of 'tempering'. Irrigated before testing, the moisture content of the root lumps is kept at a moderate range of 55% - 60%.

The physical and mechanical characteristics of plug seedlings are measured, which provides the basis for the design of transplanting mechanism. The overall measurement technology route was shown in Figure 1. Basic growth characteristics of plug seedlings were measured on 50 seedling samples per crop type. Its weight was measured by the electronic balance (Division value: 0.001 g) and the overall height by the vernier caliper (Accuracy: 0.02 mm). The limitation of the size and shape of the tray cells forces the seedling's roots to coil around the perimeter of the cells in the process of their growth, establishing adhesion forces between roots and the cell walls. Force tests of pulling seedlings under the quasistatic loading conditions were conducted with the universal testing machine (Accuracy level: 0.5) to measure the adhesion force. During the automatic transplanting operation, the seedlings' root lumps were always subjected to compression, drop, and other impacts. A a result, the compressive force of the root lumps was tested under the loading deformation of 10 mm. The corresponding peak force was used as an index to evaluate the stress-tolerant ability. The experiments were set up in a completely randomized design. Test data was recorded as shown in

Table 1.

Structure and principle

The most important factors for mechanical transplanting are that plug seedlings should be efficiently separated from their growth trays and at the same time the rhizosphere soil is less damaged during the proess of transplanting (Choi *et al*., 2002; Mao *et al*., 2014). With these considerations, a new pick-up device was designed as shown in Figure 2 for efficient transplanting. On the whole, the new pick-up device consists of an air jet loosening device, a flexible pick-up manipulator, a parallel feeding device, and a multi-axis motion control system. The loosening device was used for pushing individual seedlings upward to where they could be separated from the growth trays and grasped by mechanical grippers. The flexible pick-up manipulator was designed to move between the plug trays and the parallel feeding device for extracting, transferring, and discharging multiple seedlings. The feeding device was used to receive the extracted seedlings and deliver them in upright orientation to the planting device as needed. The control system was developed to automate the transplanting work cycle.

Figure 3 shows a complete work cycle of ejecting, extracting, transferring, and discharging multiple seedlings. The general principle is that a row of air jets installed in the loosening device are used to eject the plug seedlings from the drain holes of the tray cells. Under a certain moderate air jet power, the growth adhesion forces between the seedling's roots and the cell walls are untied for easy extraction. The pick-up manipulator then generates an appropriate path of approach and regress along which the grippers move for a cycle of extracting, transferring, and discharging multiple seedlings. In the design, it was ensured that the pick-up manipulator easily grasps a row of seedlings and precisely throws them to the feeding device. Finally, the seedling cups of the feeding device are opened one by one, which makes a planting tube to receive a free falling seedling plant. The above work cycle continues until the required transplanting work is completed.

Design of key components

Loosening device

Direct grasping of seedlings requires the high seedling quality, which is also easy to cause damages to their plants or root lumps. Besides, the polystyrene plastic trays are so soft that they can be impaled by the mechanical plunger. Combination of the mechanical plunger and the air jet ejection has provided more dependable plant removal out of tray cells under varying conditions (Shaw 1999; Han *et al*., 2019). Therefore, a loosening device was designed by combining such mechanisms or actions to separate plug seedlings, which had effectively increased plant removal. The working principle of the loosening device was to use a blast of air to blow seedlings away from their growth tray cells with minimum damage.

As shown in Figure 4a, a mechanical plunger of air jet ejection is a flexible telescopic vacuum chuck structure. It consists of a rubber air nozzle, a hollow air rod with end air intake, a compression spring, a fixed plate, a locking nut among other structural components. The air nozzle liking a pagoda structure is made of the soft silica gel material, which is the same size as the drain hole of the tray cell. In the design, the air nozzle was closely nested at the top of the air rod running through the fixed plate in the way of clearance matching. The compression spring was used to surround the air rod, which was connected in an elastic way with the air rod and the fixed plate. When the air nozzle is pushed against the bottom of the drain hole in the tray, the compression spring is indented into the support. At this point, the compression spring produces an elastic force to push the air rod in reverse. Finally, it makes the air nozzle close to the drain hole, which ensures that there is no air leakage in air jet ejection. On a high speed transplanting, whole rows of seedlings should be regularly ejected from a vertical tray as they are intercepted by individual grippers that transfer and distribute them into the feeding device. For high loosening rates, a whole row of air jets were constructed through the one-to-one drain holes of plug trays (Figure 4b). In this arrangement, plug seedlings could be loosened simultaneously in favour of efficiently picking up seedlings from their tray cells. Considering the structure stability, two lifting cylinders were set at the both support ends of a wholes row of air jets for pushing up and down.

In order to separate seedlings from the growth trays and ensure the integrity of their root lumps, it was determined that the airflow pressure of the air nozzle vent should meet the following equivalent mechanical conditions.

$$\begin{cases} P_0 \times S_0 \geq G_S + F_N \times [2F_{Q1} + F_{Q2}] \\ S_0 = \pi \times r^2 \end{cases} \tag{1}$$

where P_0 is the air pressure generated by the air jet ejection, Pa; S_0 is the ejecting core area of the air nozzle on the root lump, m^2; G_S is the gravity of the seedling, N; F_N is the adhesion forces between roots and the cell walls manifested in the vertical direction, N; F_{Q1} and F_{Q2} are the adhesion force of the side wall and the bottom of the wall, respectively, N; r is the ejecting radius of the core area of the air nozzle on the root lump, m.

Under the instant ejection operation of a row of air jets, the working force on each component in the vertical direction could be estimated as follows.

$$F_{T1} + F_{T2} = \sum_{i=1}^{N} (P_i \times S_i + G_i + F_{Si}) \quad (i=1, 2, \ldots\ldots, N) \tag{2}$$

where F_{T1} and F_{T2} are the pushing forces generated by two lifting cylinders, respectively, N; P_i is the reversed air pressure generated by the i-th air jet ejection, Pa; S_i is the reversed ejecting area of the core area of the i-th air nozzle on the root lump, m^2; G_i is the gravity of the i-th air plunger, N; F_{Si} is the elastic force to push the air rod in reverse generated by the i-th compression spring, N; N is the number of the air jet ejection.

It was assumed that the impact force and the reverse impact force of each air nozzle were equal. The reversed impact force generated by the i-th air jet ejection could be expressed as follows.

$$P_i \times S_i = P_0 \times S_0 \quad (i=1, 2, \ldots\ldots, N) \tag{3}$$

where P_i is the reversed air pressure generated by the i-th air jet ejection, Pa; S_i is the reversed ejecting area of the core area of the i-th air nozzle on the root lump, m^2; P_0 is the air pressure generated by the air jet ejection, Pa; S_0 is the ejecting area of the core area of the air nozzle on the root lump, m^2; N is the number of the air jet ejection.

It was assumed that the elastic force to push the air rod in reverse direction was equally generated by the i-th compression spring. Meanwhile, the pushing forces generated by two lifting cylinders were equal. Each air plunger was assembled in the same way. The equation 2 could be simplified as follows.

$$F_{T1} = \frac{N}{2} (P_0 \times S_0 + G_1 + F_{S1}) \tag{4}$$

where F_{T1} is the pushing forces generated by the lifting cylinder, N; P_0 is the air pressure generated by the air jet ejection, Pa; S_0 is the ejecting area of the core area of the air nozzle on the root lump, m^2; G_1 is the gravity of each air plunger, N; F_{S1} is the elastic force to push the air rod in reverse generated by each compression spring, N; N is the number of the air jet ejection.

Given the working air pressure of the lifting cylinder, its cylinder diameter could be calculated as follows.

$$D_T = \sqrt{\frac{2N}{\pi \times P_T} (P_0 \times S_0 + G_1 + F_{S1})} \tag{5}$$

where D_T is the cylinder diameter of the lifting cylinder, m; P_T is the working air pressure of the lifting cylinder, Pa; P_0 is the air pressure generated by the air jet ejection, Pa; S_0 is the ejecting area of the core area of the air nozzle on the root lump, m^2; G_1 is the gravity of each air plunger, N; F_{S1} is the elastic force to push the air rod in reverse generated by each compression spring, N; N is the number of the air jet ejection.

With the decrease of the ejecting core area of the air nozzle on the root lump, the air jet ejection needs to generate a large air pressure. Under the precondition of no air leakage in air jet ejection, there needs to be a large pushing force of the lifting cylinders while increaseing the number of air nozzles. Preliminary measurements had shown that the overall gravity of three typical seedlings grown in the 128-cell tray was about 0.12~0.14 N. And the mean adhesion forces (Table 1) were measured as 1.89 ± 0.36 N, 2.06 ± 0.44 N, and 1.87 ± 0.23 N for cucumber seedlings, pepper seedlings, and cauliflower seedling, respectively. Hence, the air ejection of the air nozzle vent was determined to be 2.64 N according to the maximum seedling weight and the maximum adhesion force. The drain cell radius at the bottom of the128-cell tray is about 2.5 mm. According to the equation 1, the air jet pressure was approximately equal to 0.11 MPa. For the theoretical calculation, the adhesion force was replaced by the pulling force. In practical applications, there may be differences in the adhesion forces between the different roots and the cell walls. There would also be some loss of pneumatic circuit pressure. Therefore, the air jet ejection should be greater than the theoretical design value. Further, the average gravity of each air plunger was measured to be about 0.5 N, and the elastic force to push the air rod in reverse was 0.2 N (Han *et al.*, 2019). In the case of the 128-cell tray, the maximum number of the air jet ejections was determined to be 16 along the length direction. According to the equation 1, the cylinder diameter of the lifting cylinder was larger than 10.65 mm when given the working air pressure of the lifting cylinder at 0.3 MPa. In the application, the cylinder diameter of the lifting cylinder could be determined according to the rounded data.

In the transplanting process, a one-time loading operation was used for a tray of seedlings. As shown in Fig. 5a, the seedling tray was pushed into the hollowed smooth rods for precise positioning of which the cylindrical diameter could just support the two adjacent tray cells. Hence, the rod frame was flat to support each row of tray cells making their drain holes exposed for air jet ejection. At the same time, a pectinate swing rod mechanism driven by a 90° oscillating cylinder was designed to firmly pressure the tray edges when ejecting seedlings. The size of the swing rod was required to be slightly lower than the spacing of the two adjacent tray cells so as not to hinder plant removal in picking. In order to loosen the seedling row after row, an industrial high-precision ball screw linear module was used to move the multiple air nozzles from one place to another (Figure 5b). The specific working process is described as follows. For ejecting seedlings, the lifting cylinder is raised up to make the multiple air nozzles close to the drain hole. As the seedlings are loosened in sequence, the lifting cylinder sets the air nozzles down. And then the ball screw linear module moves the air nozzles to the next ejecting station. In this way, the air nozzles are driven to loosen rows of plug seedlings under the combined motion control of the lifting cylinder and the ball screw linear module.

Pick-up manipulator

As plug seedlings have been loosely separated from their growth tray cells, the pick-up manipulator is easy to extract them by grasping the plant stems. Figure 6 shows a complete work cycle of approaching, grasping and extracting a seedling. A pneumatic pincette-type gripper was used to grasp the seedling stem. The gripper consists of a pair of protective pads, a pair of claws, a horizontal cylinder block, and some pneumatic connectors. Each claw rotating around a shaft was arranged on both sides of the horizontal cylinder block. When the horizontal cylinder is inflated, a pair of claws closes for grasping the seedling root lump . When the horizontal cylinder is deflated, the claws open for discharging the seedling. In order to protect the seedling stem from being hurt, a flexible pad was set on the grasping claw. The series of extracting motions were considered for successfully extracting a seedling. The opening gripper horizontally approaches the seedling on the tray cell, closes to firmly grasp the seedling stem and departs vertically from the plug tray to extract the seedling (Work trajectory: ①-②-③ in Figure 6).

In order to reliably grasp the individual seedling for a successful extraction, the operation range of the pincette-type gripper was restricted to the width of a tray cell to avoid accidentally picking a plant in an adjacent cell. It would also be desirable to have interchangeable grippers for use with different types and sizes of transplants. As shown in Figure 7a, the design dimensions of the gripper should meet the following conditions.

$$\begin{cases} d_1 + 2d_3 \le a \\ l \le a \\ d_2 \le d < d_1 \end{cases} \tag{6}$$

where a is the upper side length of the tray cell, mm; d is the outer diameter of the seedling stem, mm; d_1 and d_2 are the outer and inner opening of the gripper, respectively, mm; d_3 is the single side thickness of the claw, mm; l is the effective grasping length of the claw, mm.

Based on the basic dimensions of the tray cells and the growth characteristics of plug seedlings, the design dimensions of the gripper was determined. The cell dimension is the upper side lengths of 32 mm for the 128-cell tray. For the typical cucumbers, peppers and cauliflower seedlings, the maximum diameter ranges deviated from the center of the tray cell were measured from 10.70 mm to 18.39 mm. The grasping requirements of multiple tray cells and different seedlings should be considered. In addition, a pair of protective pads should be added to the claws to prevent damages due to the grasping action. As a result, the outer and inner opening of the gripper was designed at 20 mm and 8 mm, respectively. The single side thickness and the effective grasping length of the claw were 6 mm and 32 mm, respectively.

For the pincette-type gripper, the single grasping action has a lever effect (Figure 7b). Based on the force analysis of the lever fulcrum, the following mechanical equation can be obtained.

$$N_f \times l_1 = F_T \times l_2 \tag{7}$$

where N_f is the equivalent normal force generated by the seedling stem, N; F_T is the pushing force of the horizontal cylinder, N; l_1 and l_2 are the equivalent lengths from the fulcrum to the contact point, respectively, m.

Plug seedlings should be firmly grasped during the transplanting process. Therefore, the static friction force generated by the grasping action is at least equal to the seedling gravity and the inertial forces existed in extraction in the vertical direction.

$$F_f = G_S + F_G \tag{8}$$

where F_f is the static friction force generated by the grasping action, N; G_S is the gravity of the seedling, N; F_G is the inertial forces existed in extraction, N.

To some extent, the static friction force of the grasping action is related to the equivalent normal force generated by the seedling stem.

$$F_f = \mu_0 N_f \tag{9}$$

where F_f is the static friction force generated by the grasping action, N; N_f is the equivalent normal force in the grasping action, N; μ_0 is the coefficient of the static friction between the flexible pad and the seedling stem.

By substituting the equations 8 and 9 into the equation 7, the pushing force of the horizontal cylinder can be obtained as follows.

$$F_T = \frac{l_1}{\mu_0 l_2}(G_S + F_G) \tag{10}$$

where F_T is the pushing force of the horizontal cylinder, N; G_S is the gravity of the seedling, N; F_G is the inertial forces existed in extraction, N; l_1 and l_2 are the equivalent lengths from the fulcrum to the contact point, respectively, m; μ_0 is the coefficient of the static friction between the flexible pad and the seedling stem.

Given the working air pressure of the horizontal cylinder, its cylinder diameter could be calculated as follows.

$$D_{TH} = \sqrt{\frac{4l_1}{\pi\mu_0 l_2 P_{TH}}(G_S + F_G)} \tag{11}$$

where D_{TH} is the cylinder diameter of the horizontal cylinder, m; P_{TH} is the working air pressure of the horizontal cylinder, MPa; G_S is the gravity of the seedling, N; F_G is the inertial forces existed in extraction, N; l_1 and l_2 are the equivalent lengths from the fulcrum to the contact point, respectively, m; μ_0 is the coefficient of the static friction between the flexible pad and the seedling stem.

It was assumed that the whole transplanting process run smoothly. Hence, the inertial impact force could be negligible. The pushing force of the horizontal cylinder was mainly used to overcome the seedling's own gravity, the leaf entanglement and a certain inertia. The coefficient of the static friction between the silicone pad and the seedling stem was measured at 0.611~0.752. The equivalent length ratio for leverage was assumed to be 2:1. Therefore, the pushing force of the horizontal cylinder was calculated to be 0.49 N according to the maximum force analysis. According to the equation 11, the cylinder diameter of the horizontal cylinder was larger than 1.44 mm when given the working air pressure of the lifting cylinder at 0.3 MPa. It is clear that a smaller horizontal cylinder under a lower working pressure can be used to easily pick up seedlings.

For automatic extraction of a whole row of seedlings, an integral part had to be designed with special multi grippers. As shown in Figure 8a, the multi grippers were arranged in a row and fixed on the 1640 type flat aluminium profile (the thickness of 16 mm and the width of 40 mm). The installation number and interval distance of the seedling grippers could be adjusted to correspond to different specifications of the tray cells. The flat aluminium profile was assembled on the 4040 type square aluminium profile (the thickness and width of 40 mm) with an end-to-end detachable connection, which could adjust the inclining angle of the grippers in approaching the seedlings. The inclined design also helps the seedlings to slide off when they are discharged. In agricultural production, different sizes of plug trays may be used to cultivate seedlings. When the mounting dimensions of the pincette-type gripper (D_S in Figure 8b) are within the scale of a single tray cell (D_T in Figure 8b), the whole row of multi grippers could be constructed through the one-to-one way. Otherwise, it is necessary to set an interval space for the dislocated assembly of multi grippers, which can also reduce the tangling of foliage between the seedlings. As shown in Figure 8b, the extraction operation of an interval row of multi grippers needs to be divided into two times: first to extract odd bits, and second to take even bits. Hence, a horizontal pusher was selected for the inter-leaved operation of grasping seedlings. Finally, the multi-gripper system can complete the required seedling extraction through a kind of horizontal pushing dislocation.

As shown in Figure 9, an X-Y Cartesian coordinate pick-up manipulator consisting of two synchronous belt linear actuators and two rodless cylinders was designed to locate the work position of multi grippers. The linear actuators of the same construction were mounted side by side in the horizontal direction, which were connected through one long shaft. Each linear actuator was supported by the light-weight aluminium alloy wires, and two limit positioning sensors were allocated, and one start positioning sensor was used to detect the zero position. On the input power, the linear actuator was driven by a stepper motor allocated with a high-performance servo driver. On the effective stroke, the total effective motion length of the linear actuators should meet the working space of extracting seedlings. The rodless cylinders were installed at the vertical direction, which was straightly hung onto the sliders of two horizontal linear actuators. Each rodless cylinder was equipped with an oil buffer at both ends to avoid collisions and adjust the lifting height of the grippers. The multi grippers were fixed onto the sliders of the rodless cylinders. The overall gripper trajectory was designed for the efficiency of the point-to-point drive and minimum control requirements. Thus, the horizontal linear actuators can move the multi grippers back and forth between the plug tray and the feeding device, which is used for approaching and transferring seedlings (Work trajectory: ①-③ in Figure 9). The vertical rodless cylinders are used to move the multi grippers up and down for extracting and discharging seedlings (Work trajectory: ②-④ in Figure 9).

Feeding device

The function of the feeding device was used to receive the extracted seedlings and deliver them one by one to the planting device as needed. In the structure design, the feeding device was closely integrated with the whole row of seedling pick-up manipulator (Figure 10a). There were several seedling cups corresponding to multi grippers. The bottom of each seedling cup was equipped with a double-door valve mechanism for closing to receive seedlings and opening to deliver them. The valve mechanism likened to be a typical crank-slider mechanism consists of a mini cylinder, a hinged joint, a pair of linkages, a pair of crank-type valves, and some connecting parts. The mini cylinder mounted in alignment was equivalent to the slider. The linkages were used to connect the mini cylinder with the crank-type valves.

In order to reliably receive the individual seedling, the inner cavity of the seedling cup should be able to accommodate the whole plant placed at the maximum angle. As shown in Figure 10b, the design dimensions of the seedling cup should meet the following conditions.

$$\begin{cases} m \geq \sqrt{2} \times a + 2\Delta d \\ h \geq h_s \end{cases} \quad (12)$$

where m is the side length of the seedling cup, mm; a is the upper side length of the tray cell, mm; Δd is the reserved safety gap, mm; h is the effective height of the seedling cup, mm; h_S is the effective height of the seedling and its root lump, mm.

In the design of opening-closing mechanism of the seedling cup, the effective pushing stroke of the mini cylinder should meet the 90° swing requirement of the crank-type valve. According to the triangle relation and the length requirements for each rod of the offset crank-slider mechanism, the following opening-closing dimension analysis could be obtained.

$$\begin{cases} r \times \cos\alpha + l \times \sin\beta_1 = e \\ l \times \sin\beta_2 = e \\ S = r \times (\sin\alpha + \cos\alpha) + l \times (\cos\beta_1 - \cos\beta_2) \\ l \geq r + e \end{cases} \quad (13)$$

where r is the crank length from point A to point B, mm; l is the linkage length from point B to point C, mm; e is the offset distance of the crank-slider mechanism, mm; S is the effective pushing stroke of the mini cylinder, mm; α (∠BAO) is the initial mounting angle of the crank-type valve, °; β_1 (∠BCO) and β_2 (∠B'C'O) are the angles of the linkage motion in the vertical direction, respectively, °.

Following up from equation 13, the effective pushing stroke of the mini cylinder can be calculated as follows.

$$S = r \times (\sin\alpha + \cos\alpha) + \sqrt{l^2 - (e - r \times \cos\alpha)^2} - \sqrt{l^2 - e^2} \quad (14)$$

where S is the effective pushing stroke of the mini cylinder, mm; r is the crank length from point A to point B, mm; l is the linkage length from point B to point C, mm; e is the offset distance of the crank-slider mechanism, mm; α (∠BAO) is the initial mounting angle of the crank-type valve, °.

The design of the seedling cup should be able to accommodate small variations in dimensions of the 128-cell and 72-cell common trays. According to the 40 mm cell dimensions of the 72-cell tray, the side length of the seedling cup was determined to be greater than 56.57 mm. Therefore, the 60 mm square tube could be used as the seedling cup, which had a reserved safety gap of 1.7 mm. It was also suitable for the dislocated assembly of multi grippers for 128-cell tray. The overall seedling heights were measured at 145.24 ± 5.11 mm, 190.59 ± 10.26 mm, and 127.11 ± 6.37 mm for cucumber seedlings, pepper seedlings, and cauliflower seedlings, respectively. Therefore, the effective height of the seedling cup was designed at 300 mm accommodating the three vegetable seedlings used in this study. To make room for seedlings that can easily fall off, a bell-mouth guiding tube was nested over the cup. It was assumed that the crank-type valve was mounted flat and had half of the double-door length. The crank length of 15 mm was equal to a quarter of the side length of the seedling cup, and its initial mounting angle was 0°. Since the mini cylinder was mounted on the vertical center line of the seedling cup, the offset distance of the crank-slider mechanism was equal to half of the side length of the seedling cup. According to the basic requirements of the crank-type valve rotation, the linkage length was set to be the sum of the crank length and the offset distance. Accordingly, the linkage length from point B to point C was equal to 45 mm. By substituting the above data into the equation 14, it was calculated that the effective pushing stroke of the mini cylinder was about 23.88 mm. In the application, an effective pushing stroke could be determined according to the rounded data. Due to the seedling's light weight and the limited falling height, the falling impact would not be too great. Therefore, an ordinary mini cylinder can be used for closing and opening the double-door valves.

In order to mitigate the possible fall impact, a flexible cushion rubber could be set on the contact part of the crank-type valve. Further, there are different ways to feed seedlings according to the configuration of the planting device. As shown in Figure 11, the feeding device by using guiding drop tubes could be divided into half to deliver the seedlings when there were two planting devices. If the machine had four planters, it needed to further subdivide the feeding device. It could be seen that the delivering ability would be weakened when the feeding device was excessively grouped. The number of individual feeding units could be also appropriately increased in order to pick up more plug seedlings at a time.

Control system

According to the planned seedling pick-up requirements, the control system should manipulate the related mechanical mechanisms to continuously complete the work cycle of ejecting, extracting, transferring, and discharging multiple seedlings. Consequently, an electric control system was designed as shown in Figure 12. It consists of a multi-axis motion controller, two stepper-driver units, five pneumatic control units, several positioning sensors/switches, and some other electrical/pneumatic cables. The multi-axis motion controller was used as the host unit for programming and communicating with other electronic components. The seedling loosening, grasping, and discharging operations were taken as the pneumatic porcesses. Compressed air after treatment with a filter regulator/lubricator combination was used to supply the air flow power to the pneumatic execution units. The corresponding solenoid control valve was made to either execute the inlet and outlet actions. The air jets were driven by 3 ports and 2 positions solenoid control valves, and those double-acting cylinders were driven by 5 ports and 2 positions solenoid control valves. The inlet path of each pneumatic actuator is constantly adjusted by an overflow-relieve valve in order to meet different working pressures of the cylinders, and the outlet is installed by an exhaust silencer throttle valve for different working speeds. The cylinder limit position was designed with multichannel switch status detection and on-off controls, which can respond to the operating action in time.

On the basis of saving cost, the horizontal reciprocated linear motion of the grippers and the air jets was driven by the closed-loop stepper motor. In order to eliminate motion errors efficiently, an S-shape acceleration-deceleration method was adopted for the speed control process. The corresponding starting and limiting locations were incorporated with several positioning sensors. A user-friendly touching screen was designed to set some working parameters such as the amount of displacement and velocity in operation, I/O action timing, sensing status check, and the rows/column settings. Finally, the control operation of each working unit was coordinated by several sensors arranged with the needed detection positions. Some movements and location information were sent as feed back to the control unit to make the user decide whether the corresponding action should be performed or not. The efficient pick-up device had the flexible automatic transplanting of plug seedlings with a combination of mechanical, electrical and pneumatic technical means.

Performance test

As shown in Figure 13, a prototype of the efficient pick-up device was constructed to examine whether its working efficacy was satisfactory or not. The appropriate industrial vacuum chuck from Quanlifa Robot Technology Co., Ltd., Suzhou, China, was used to loosen the seedlings with air jet ejection. The clamping fixtures commonly used in the injection molding manipulator were selected as the end-effector for picking up seedlings. The CCM-W50-25 type belt and ballscrew driving linear actuators from Dongguan Yuancheng Automation Equipment Co., Ltd., Guangdong, China, were used to build the horizontal reciprocating movement. The cylinder actuators were purchased and assembled from SMC Corporation and Taiwan Airtac International Group. The operating air pressure of the cylinder actuators was adjusted to ensure an optimum grasping force of the gripper and a proper lifting speed for seedling extraction. The main structure was constructed with aluminum profiles, and the related supporting parts were customized according to the design requirements. Finally, the testing prototype for the 128-cell tray had 16 air nozzles for ejecting, 8 seedling grippers for extracting, and 8 seedling cups for discharging. An M2S multi-axis motion controller from TOPCNC Automation Technology Co., Ltd., Beijing, China, was used as the host unit with the form-filling programming. The controller using a 32-bit high precision microprocessor is for the 4-axis motion system. It has 28 inputs and 22 outputs of independently programmed setting, and its pulse frequency reaches 400 KHz. Several corresponding electric assisting elements and some pneumatic elements were designed and equipped for the control system. According to the working requirements of ejecting and grasping seedlings, the control software was programmed.

In the evaluation, a success ratio (SR) in picking up seedlings represents how successfully the device performs ejecting, extracting, transferring, and discharging of seedlings (Choi *et al*., 2002; Mao *et al*., 2014). If the seedling was not loosened by the air jet ejection, it was considered that the seedling had not successfully been separated from the growth tray cell. This loosening failure was considered as a kind of functional failure. When more than 1/4 of the root lump as a whole was broken, or the seedling was ejected in the outside of the tray cell, they were also judged as the loose failures. In the same way, some extracting and delivering failures were the manifestation of unsuccessful seedling picking, which was also considered as functional failures. Besides, if the leaf damage had some effects on vegetable growth after transplanting, it was considered as seedling damage. Taking these cases into consideration, the success ratio (SR) in picking up seedlings was defined as follows.

$$\mathrm{SR}\,(\%) = \frac{N_1 - N_2 - N_3 - N_4}{N_1 - N_2} \times 100 \qquad (16)$$

where SR is the success ratio in picking up seedlings, %; N_1 is the number of seedlings fed; N_2 is the number of missing seedlings; N_3 is the number of some functional failures (no loosening from the tray cell, more than 1/4 of soil breakage, the seedling ejected in the outside, and no seedlings discharged into the cup); N_4 is the number of seedling damages in transplanting (the stems torn by the gripper).

The performance tests were conducted at the Key Laboratory of Modern Agriculture Equipment and Technology, Ministry of Education, Jiangsu University, China. The test objects were typical vegetable plants such as cucumber seedlings, pepper seedlings, and cauliflower seedlings. There might be an optimum range of the root lump's moisture content which would facilitate the air jet ejection of seedlings (Ryu *et al*., 2001; Han *et al*., 2019). The seedlings were watered a day before testing. The moisture contents of the root lumps were progressively controlled at 4 levels of

50-55%, 55-60%, 60-65%, and 65-70%, respectively. In the previous studies, the best intact rate succeeding in loosening root lumps was achieved when the air jet pressure was 0.2 MPa, the airflow circuit was fully open at the outlet of 4 mm, and the air jet had no sponges (Han *et al*., 2019). In this paper, a whole row of air jets was designed for a high loosening rate through the one-to-one drain holes. Therefore, the different loosening ways were evaluated with the one-time ejection for a whole row of seedlings and the individual ejection in rapid sequence. A suitable air gripper and its working pressure had been determined according to theoretical analysis. Further, the pick-up quality under different cushioning protective layers was investigated such as the sponge pad and the rubber pad. The previous study showed that the picking speed of a single gripper was 16 plants/min when the similar linear modules and cylinder mechanism was used for extracting seedlings (Mao *et al*., 2014). In this study, there were 8 grippers for picking, which greatly improved the transplanting efficiency. It was intended at the beginning of the study to concentrate most efforts on making the function of the seedling pick–up device more accurate. Therefore, 2 levels of picking quantities were set at a low frequency state of 120 plants/min and a relatively high state of 140 plants/min.

Based on the above analysis, there were 3 types of test objects (cucumber seedlings, pepper seedlings, and cauliflower seedlings), 4 levels of moisture contents (50-55%, 55-60%, 60-65%, and 65-70%), 2 types of loosening ways (one-time ejection and individual ejection), 2 types of protective layers (the sponge pad and the rubber pad) and 2 levels of picking quantities (PF: 120 plants/min and 140 plants/min). In the end, the L_{24} ($3^1 \times 4^1 \times 2^4$) type orthogonal table was used according to these sets of factors and levels. The last column was considered as an error, and the success ratio (SR) in picking up seedlings was used as the evaluation index. There were 24 tests. Each test had one tray of seedlings transplanted continuously and the process was repeated 20 times. In order to obtain verifiable results, the transplanting process was observed and recorded on site using a CCD camera. The corresponding statistical analysis was conducted on SPSS 18.0 (SPSS Inc., Chicago, IL, USA). Duncan's new multiple range method ($\alpha = 0.05$) was used in multiple comparisons when the significant differences exist.

Results and Discussion

Means of 5 factors and several levels orthogonal design experiments were used to study the effects of automatic transplanting. The results of the orthogonal experiments were shown in Table 3. Viewed from the range analysis, the primary and secondary factors in the tests were the root lump's moisture content and the test object, followed by the different loosening way, the different protective layer and the picking quantity. The optimal level group was $A_2B_2C_2D_2E_1$. When the test object was the pepper seedling, the moisture content was around 55% to 60%, the loosening way was the individual ejection one by one, the protective layer was the rubber pad, and the picking quantity was set at 120 plants/min, the optimum seedling pick-up effect could be achieved.

Further, the statistical analysis of variance (ANOVA) (Table 4) showed that the test object, the root lump's moisture content and the loosening way had significant effects ($0.01<p<0.05$) on the success ratio in picking up seedlings, and the other factors had no significant effects ($p>>0.05$). It was consistent with the results obtained from the range analysis for the orthogonal tests. Both the seedling growth factors and the mechanical operating parameters could affect seedling pick-up efficiency.

In the process of the seedlings' growth, the adhesion forces have been established between roots and the cell walls. As a result, they can be efficiently separated from the growth trays by the air jets ejection. It is easy to extract them by grasping the plant stems. However, different seedlings have different growth characteristics (Lim *et al*., 2017). It was found that the stems of these cucumber seedlings were often quite brittle, which may easily get hurt by the grippers (Mao *et al*., 2014). Compared to pepper and cauliflower seedlings, the lowest success ratio for picking up cucumber seedling was 88.89%. The tests confirm that the sturdy seedling plants are necessary for mechanized transplanting (Shaw, 1993; Lim *et al*., 2017). For the fragile seedlings, soem appropriate days of 'tempering' were needed to strengthen the stem hardness (Mao *et al*., 2014). The success ratios in picking up seedlings for the different moisture contents were 89.29%, 92.00%, 91.77%, and 87.45% for 50%-55%, 55%-60%, 60%-65%, and 65%-70%, respectively. Obviously, the success rate at the medium level of soil moisture content was significantly better than other levels (Ryu *et al*., 2001; Mao *et al*., 2014). As the air jet ejection is used to loose the root lump for seedling extraction, the root system becomes a major component for bearing force. Much too dry and wet root lumps of plug seedlings are often quite loose and soft, which makes them difficult for the air jets to eject them (Han *et al*., 2019). It would further need to study the root-soil composite mechanical properties and their interaction with water. On the whole, the loosening effect of the individual ejection one by one was better than that of the one-time ejection for a whole row of seedlings. When 16 air nozzles were used for the air ejection at the same time, their air consumption was quite large. As a result, it was difficult to ensure a stable jet pressure in long-term use (Han *et al*., 2019; Mao *et al*., 2020). The success ratios in picking up seedlings for the soft sponge pad and the hard rubber pad were 89.78% and 90.48%, respectively. There was no significant difference in the quality of seedlings extraction under the two protective layers. In the actual production, the different protective pads should be used for the seedling stems with different texture. To use the manipulator with various types of plants, an interchangeable set of specialized grippers would be also desirable. The success rate of automatic picking was found to be independent from the work speed. However, the whole device could run stably for the majority of tests under a low frequency operation of 120 plants/min. The high-speed operation would have a large inertia impact, which affected the overall qualities of picking up seedlings (Mao *et al*., 2014). To sum up, the horticultural and mechanical factors affecting the percentage of successfully picking up seedlings from the cells were varied at different levels (Shaw, 1993; Mao *et al*., 2014; Lim *et al*., 2017; Mao *et al*., 2020). The deep integration of the pick-up device and the seedling qualities should continue to be further strengthened for realizing the full potential of automatic transplanting (Parish, 2005).

As shown in Figure 14, the operation process of the efficient pick-up device for automatic transplanting was analyzed. Under those normal production conditions, a row of plug seedlings were ejected for getting rid of adhesion. And then row after row of seedlings were picked up from their tray cells (Figure 14a). There was no damage to plug seedlings and their root-soil integrity was well maintained. The corresponding peak force under the loading deformation of 10 mm were measured at 32.95 ± 6.31 N, 34.03 ± 5.32 N, and 31.06 ± 5.47 N for cucumber seedlings, pepper seedlings, and cauliflower seedling, respectively. Once the loose seedling substrate is tangled by the root system, the formed root lumps can withstand some mechanical actions. This provides the possibility for high-speed mechanized transplanting. Even if there was damage, it was mainly at the bottom of the root lump and had little effect on later growth of the seedling. In cultivation, the appropriate management of water and fertilizer nutrition could quickly make up for the adverse growth caused by damage (Lim *et al*., 2017; Han *et al*., 2022). To a certain extent, the production efficiency was found to depend on the condition of the plug seedlings within the trays. When the blank cells and unhealthy seedlings existed, some missing failures to pick up plug seedlings would occur. The seedling stems were so curved or lodged that the gripper could not catch them (Figure 14b). If these unhealthy or missing seedlings in the trays could be filled by another sensing robotic transplanter, the automatic picking performance would be better (Mao *et al*., 2014; Tong *et al*., 2013; He *et al*., 2017). A vision system might also be used to guide the manipulator to the plants (Ting *et al*., 1992; Ryu *et al*., 2001). The use of this device including the multi-step decomposing operation required that the seedlings were sturdy with the well-developed root system. Otherwise, the seedling's root soil was vulnerable to damage, which would affect transplanting quality and later growth (Figure 14c). Sophisticated features like force control for ejection and extraction could be used for flexible transplanting. In this case, the pick-up device should be relatively expensive, which affects its practical application.

Under the actual production conditions, the performance tests were conducted to verify the optimal machine operation parameters. In the test trials, plug seedlings from the 128-cell trays were automatically transplanted. Each test was repeated five times with one day interval. The results of the performance tests were shown in Table 5. The success ratios for picking up seedlings were 90.75%, 94.49%, and 92.61% for cucumber seedlings, pepper seedlings, and cauliflower seedlings, respectively. For the three seedlings, the failures of air jet ejection and extraction were similar. There were 15 discharging failures in cucumber seedlings. The reason was that the crown widths of cucumber were so broad that their leaves often tangled with the gripper and the cup (Mao *et al*., 2014). Finally, the seedlings could not be accurately delivered into the cups. The discharging accuracy of the seedlings might be improved by increasing their vertical falling inertia. Some damage cases mainly included the root-soil breakages. When the seedling roots were not well developed throughout the tray cells or the roots had grown out of the polystyrene tray material, the root lumps might be loosened by the air jets and not be regularly ejected (Han *et al*., 2019; Mao *et al*., 2020; Tian *et al*., 2022). In general, the vegetable transplants need be stocky and green with a well-developed root system. At the same time, the roots should be evenly distributed in the rhizosphere soil or substrate so that the root lumps are not broken during transplanting (Tong *et al*. 2013; Mao *et al*., 2014; Lim *et al*., 2017). This will help they can tolerate a certain mechanical actions and continue growing to achieve optimum yield. On the whole, the new pick-up device can efficiently complete the work cycle of ejecting, extracting, transferring, and discharging multiple seedlings. It is easily adapted to different soft tray sizes through multiple configurations. Compared with the single-gripper structure, the designed pick-up device has high capacity because whole rows of seedlings are removed at one time (Tsuga 2000; Ryu *et al*., 2001; Choi *et al*., 2002; Cui *et al*., 2013; Mao *et al*., 2014; He *et al*., 2016; Jin *et al*., 2018). In addition,, the air nozzles and grippers are adjustable, and the seedling cups may be re-assembled. If the multiple grippers or seedling cups are designed as a variable mechanism with different interval, the new pick-up device can perform various tasks by changing mainly the software and requiring minimum change on the hardware.

Conclusions

On basis of cultural practice for vegetable production, an efficient pick-up device was developed by the multi-step decomposing operation of ejecting, extracting, transferring and discharging the seedlings. In the structure design, the loosening device using air jets to eject seedlings was designed to separate them from the vertical growth trays. The multi-grippers were arranged for automatic extracting of whole row of seedling. The feeding device was closely integrated with the whole row of seedling pick-up manipulator. As the first prototype was constructed, the performance tests were conducted to find out the optimal operation parameters and transplant production conditions. The testing results showed that the test object, the root lump's moisture content and the loosening way had the significant effects on the success ratio in picking up seedlings. When the test object was the pepper seedling, the moisture content was around 55% to 60%, the loosening way was the individual ejection one by one, the protective layer was the rubber pad, and the picking quantity were set at 120 plants/min, the optimum seedling pick-up effect could be achieved. Under the optimal level group, the maximum success ratio for automatic picking up seedlings was up to 94.49% for pepper seedlings. The designed seedling pick-up device operated well at a speed of 120 plants/min except for few root-soil damages. The deep integration of the pick-up device and the seedling qualities should further be strengthened in future work in order to realize the full potential of automatic transplanting.

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Table 1. Basic characteristics of typical vegetable plug seedlings.

Seedling	Seedling age (day)	No. of leaves	Stem diameter (mm) [a]	Seedling height (mm)	Seedling weight (g)	Adhesion force (N)	Peak compressive force (N)
Cucumber	21	2~3	3.15±0.15	145.24±7.11	13.57±0.14	1.89±0.36	32.95±6.31
Pepper	42	5~6	2.56±0.11	190.59±9.26	13.62±0.11	2.06±0.44	34.03±5.32
Cauliflower	30	4~5	1.88±0.13	127.11±6.37	12.96±0.12	1.87±0.23	31.06±5.47

[a] Data is mean ± std. dev.

Table 2. Factors and levels of the orthogonal optimum tests.

Factors (levels)	A: test object	B: moisture content (%)	C: loosening way	D: protective layer	E: picking quantity (plants/min)
1	Cucumber	50-55	One-time ejection	Sponge pad	120
2	Pepper	55-60	Individual ejection	Rubber pad	140
3	Cauliflower	60-65	--	--	--
4	--[a]	65-70	--	--	--

[a] The symbol (--) indicates null.

Table 3. Results and range analysis of the orthogonal tests.

Experiment No.	Factor (levels)					Null	Success Ratio (%)
	A (3)	B (4)	C (2)	D (2)	E (2)		
1	1 (Cucumber)	1 (50-55%)	1 (One-time ejection)	1 (Sponge pad)	1 (120 plants/min)	1	87.18
2	1	2 (55-60%)	1	1	2 (140 plants/min)	2	91.53
3	1	3 (60-65%)	2 (Individual ejection)	1	2	1	90.61
4	1	4 (65-70%)	2	1	1	2	87.87
5	1	1	2	2 (Rubber pad)	2	2	86.75
6	1	2	2	2	1	1	92.59
7	1	3	1	2	1	2	92.24
8	1	4	1	2	2	1	82.38
9	2 (Pepper)	1	1	1	1	2	88.82
10	2	2	1	1	2	1	92.56
11	2	3	2	1	2	2	93.34
12	2	4	2	1	1	1	88.57
13	2	1	2	2	2	1	93.51
14	2	2	2	2	1	2	94.38
15	2	3	1	2	1	1	92.21
16	2	4	1	2	2	2	88.27
17	3 (Cauliflower)	1	1	1	1	2	87.19
18	3	2	1	1	2	1	89.57
19	3	3	2	1	2	2	90.67
20	3	4	2	1	1	1	89.39
21	3	1	2	2	2	1	92.28
22	3	2	2	2	1	2	91.37
23	3	3	1	2	1	1	91.56
24	3	4	1	2	2	2	88.24
K1	88.89	89.29	89.31	89.78	90.28		
K2	91.46	92.00	90.94	90.48	89.98		
K3	90.03	91.77	--	--	--		

K4	--	87.45	--	--	--		
Range	2.56	4.55	1.63	0.71	0.31		
Primary factors	B>A>C>D>E						
Optimal level	$A_2B_2C_2D_2E_1$						

Table 4. Analysis of variance (ANOVA) for the orthogonal tests.

Source	Sum	DOF[a]	Mean Square	F value	p value	Significant Test[b]
A: test object	26.40	2	13.20	4.2234	0.0351	*
B: moisture content	84.39	3	28.13	9.0006	0.0012	*
C: loosening way	15.97	1	15.97	5.1112	0.0391	*
D: protective layer	3.00	1	3.00	0.9587	0.3430	ns
E: picking quantity	0.56	1	0.56	0.1786	0.6786	ns
Deviation	46.75	14	3.34			
Sum	177.07					

[a] Degree of freedom; [b] ns, no significant effect; * Significant level at $0.01<p<0.05$.

Table 5. Results of performance tests under the actual production conditions.

Seedling	No. of seedling fed	No. of missing seedlings	No. of ejecting failures	No. of extracting failures	No. of discharging failures	No. of damage failures[a]	Success ratio[b] (%)
Cucumber	640	2	10	9	15	25	90.75
Pepper	640	5	6	6	7	16	94.49
Cauliflower	640	4	7	8	9	23	92.61

[a] Damage failures: soil breakage and seedling damage; [b] Success ratio: the percentage of succeeding in picking up seedlings from the trays and discharging them to the cups.

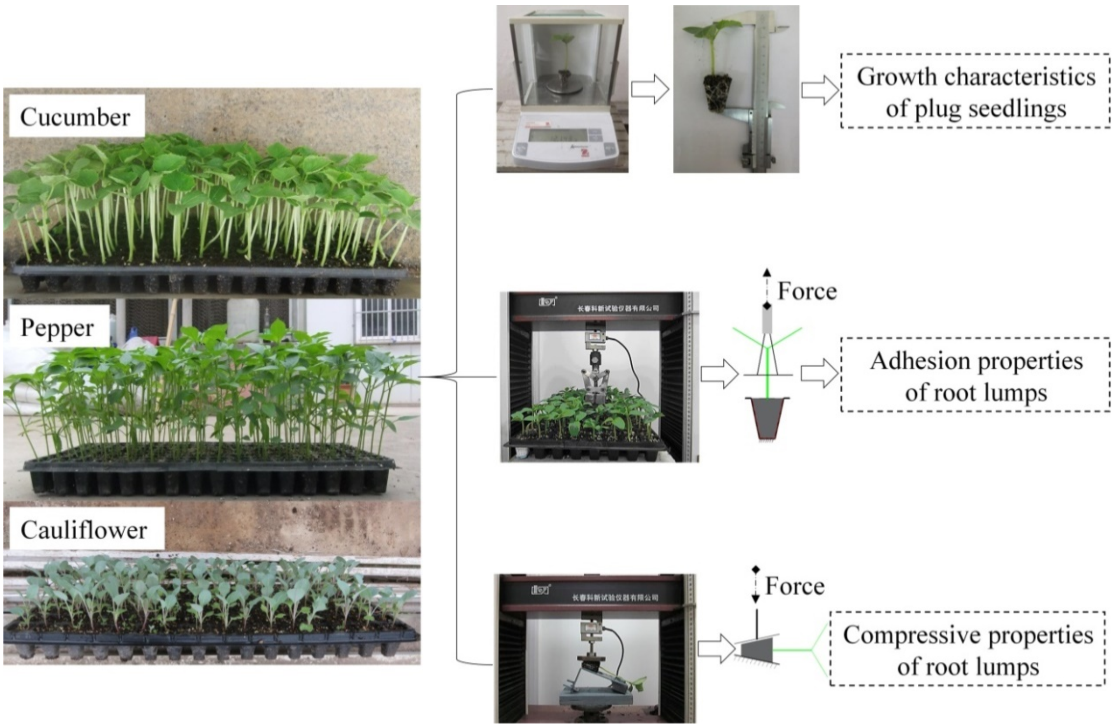


Figure 1. Growth characteristics and mechanical properties of typical vegetable plug seedlings.

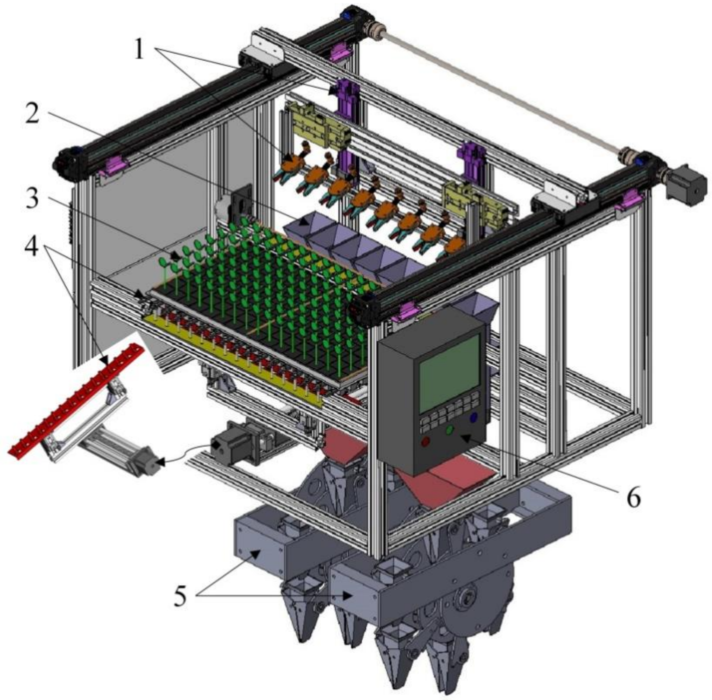


Figure 2. Structure drawing of the new pick-up device for efficient transplanting: (1) pick-up manipulator; (2) feeding device; (3) plug seedling; (4) loosening device; (5) planting device; (6) control system.

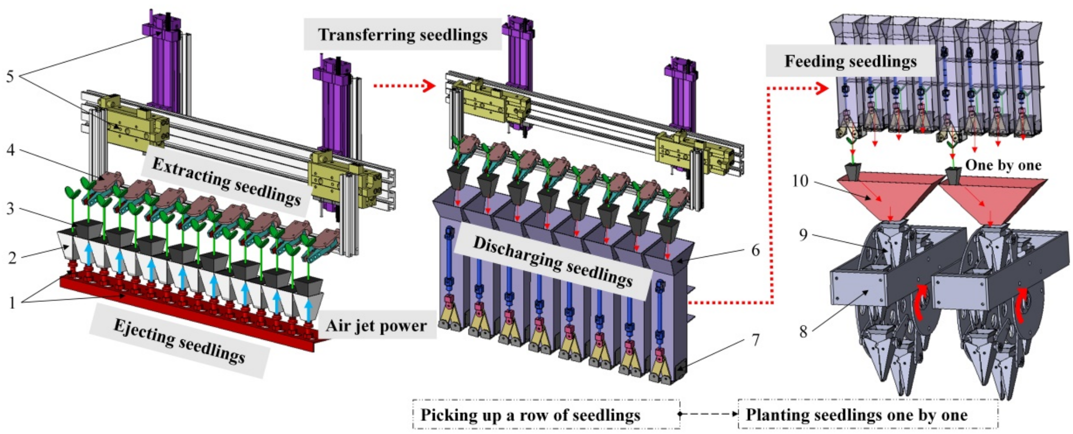
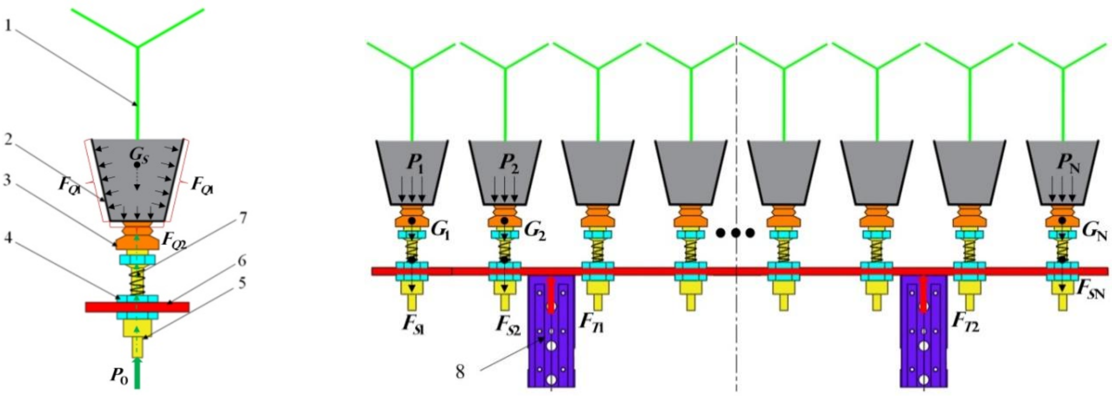
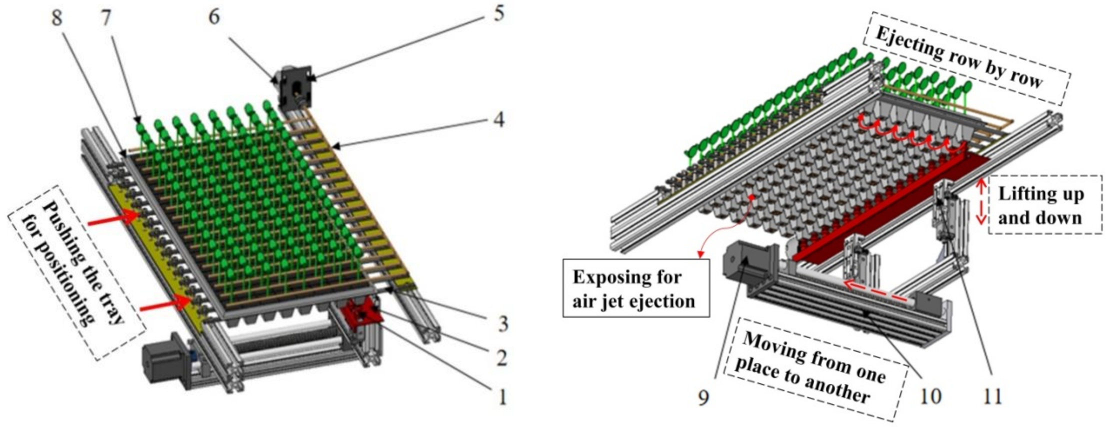


Figure 3. Work cycle of ejecting, extracting, transferring, and discharging multiple seedlings: (1) air jets; (2) tray cell; (3) plug seedling; (4) gripper; (5) transplanting manipulator; (6) seedling cup; (7) opening and closing valve; (8) planting device; (9) planting tube; (10) guiding drop tube.



(**a**) The structure shape of the air nozzle (**b**) The force diagrams of multiple air nozzles

Figure 4. Structure drawing and force diagrams of the air jets ejection: (1) plug seedling; (2) tray cell; (3) rubber air nozzle; (4) locknut; (5) air rod; (6) fixed plate; (7) compression spring; (8) lifting cylinder.



(**a**) Positioning structure drawing of plug trays (**b**) Moving structure drawing of multiple air nozzles

Figure 5. Structure drawing of the loosening device for positioning and moving: (1) multiple air nozzles; (2) fixed plate; (3) smooth rod; (4) swing rod; (5) supporting seat; (6) 90-degree oscillating cylinder; (7) plug seedling; (8) plug tray; (9) motor; (10) ball screw linear module; (11) lifting cylinder.

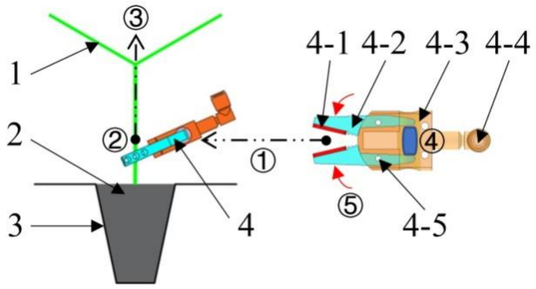
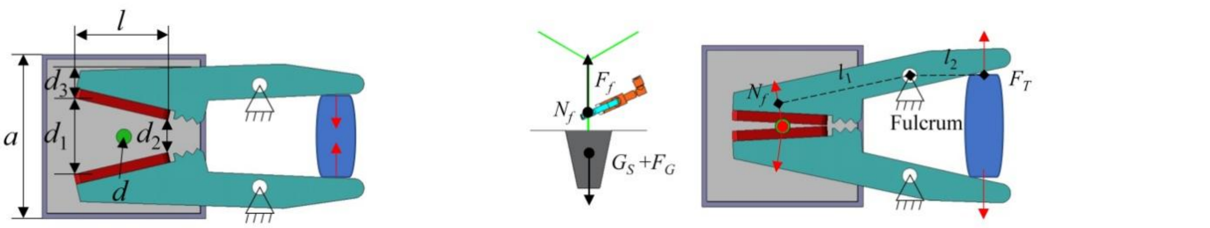
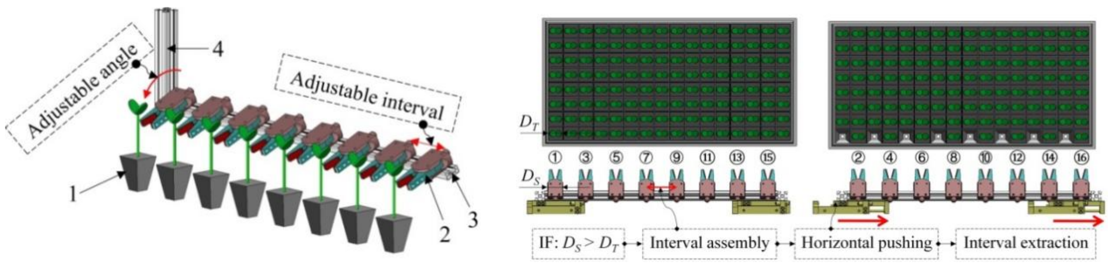


Figure 6. Schematic diagram of the gripper for grasping the seedling: (1) seedling stem; (2) root lump; (3) tray cell; (4) pincette-type gripper; (4-1) protective pad; (4-2) claw; (4-3) horizontal cylinder block; (4-4) quick connector; (4-5) rotating shaft; ①-approaching the seedling; ②-grasping the stem ; ③-extracting the seedling; ④-maintaining air inflation; ⑤-closing for grasping.



(**a**) Dimension drawing of the gripper (**b**) Force diagrams of grasping the seedling

Figure 7. Dimension drawing and force diagrams of the gripper for grasping the seedling.



(**a**) Structure design of multi grippers (**b**) Interleaved operation of grasping seedlings

Figure 8. Structure drawing and operation of multi grippers for grasping whole rows of seedlings: (1) plug seedling; (2) seedling gripper; (3) 1640 type aluminium profile; (4) 4040 type aluminium profile.

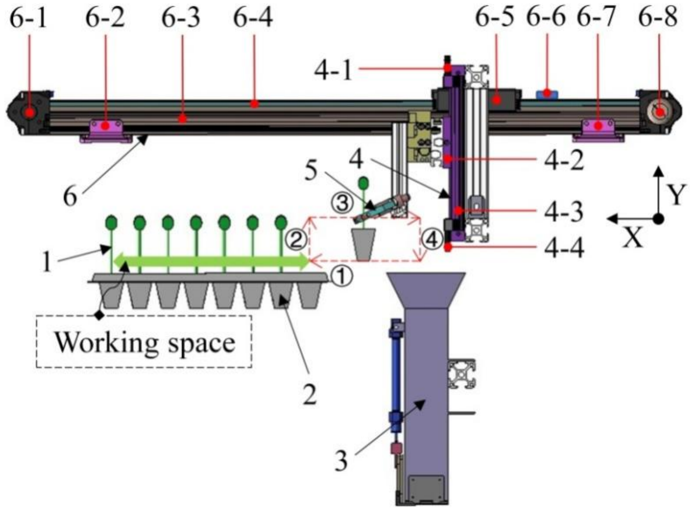
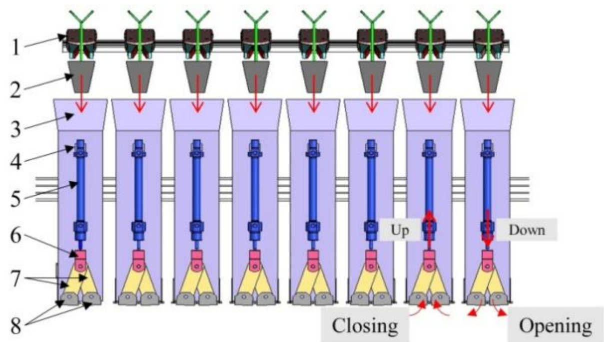
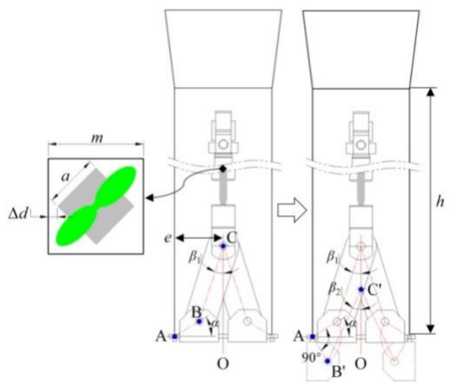


Figure 9. Structure drawing of a Cartesian coordinate pick-up manipulator: (1) plug seedling; (2) plug tray; (3) feeding device; (4) rodless cylinder; (4-1 & 4-4) oil buffer; (4-2) cylinder block; (4-3) cylinder slider; (5) multi grippers; (6) linear module; (6-1) tailstock; (6-2 & 6-7) limit positioning sensor; (6-3) rail beam; (6-4) synchronous belt; (6-5) module slider; (6-6) start positioning sensor; (6-8) input shaft assembly; ①-approaching the seedling; ②-extracting the seedling; ③-transferring the seedling; ④-discharging the seedling.





(**a**) Structure design of the feeding device (**b**) Dimension analysis of the mechanism

Figure 10. Structure drawing and dimension analysis of the parallel feeding device: (1) multi grippers; (2) plug seedling; (3) seedling cup; (4) tailstock; (5) mini cylinder; (6) hinged joint; (7) linkage; (8) crank-type valve.

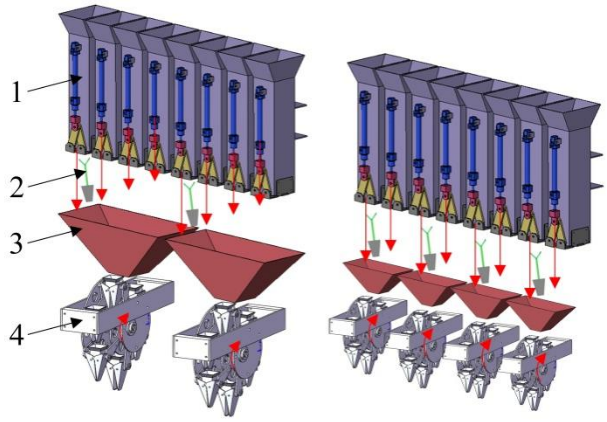


Figure 11. Structure drawing of the feeding device working for various planting: (1) feeding device; (2) plug seedling; (3) guiding drop tube; (4) planting device.

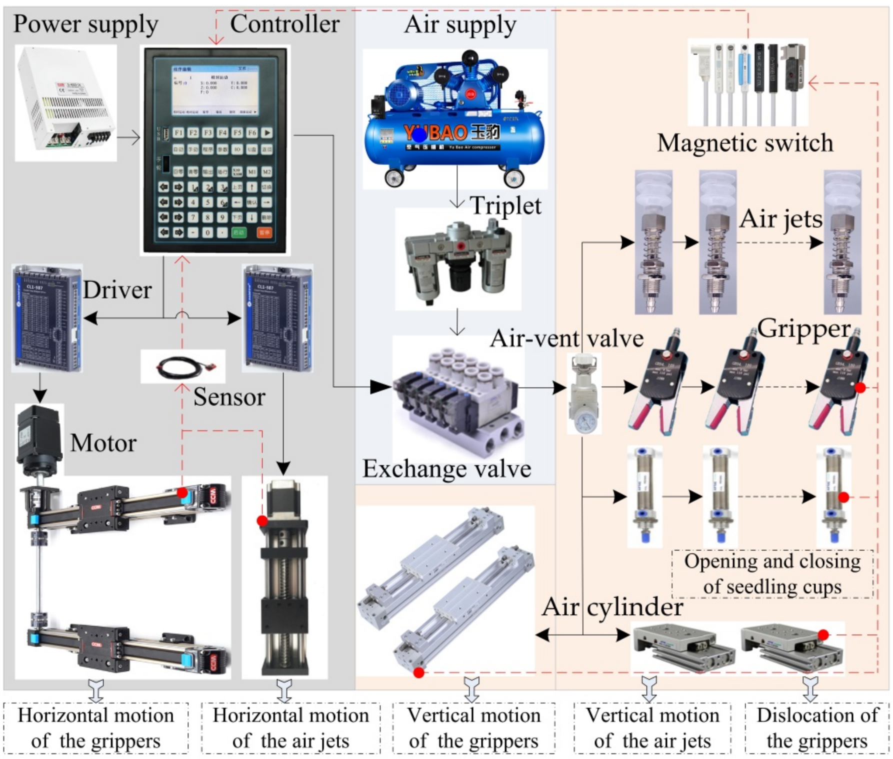


Figure 12. Control system structure drawing of the efficient pick-up device.

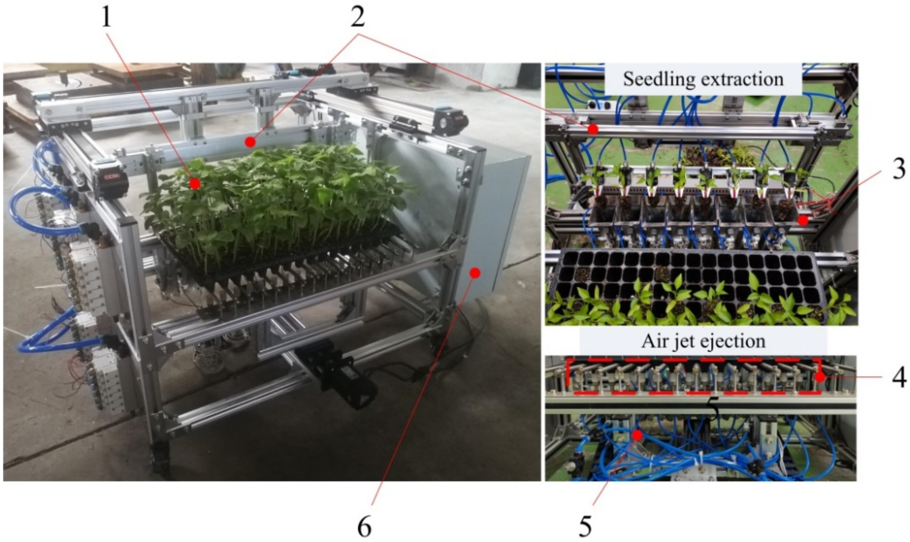
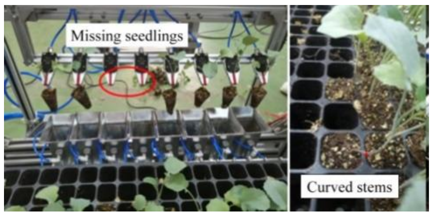
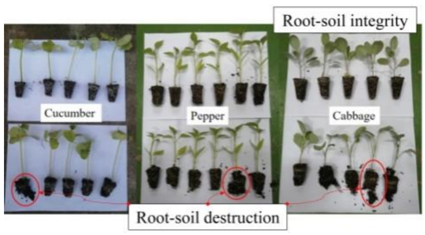


Figure 13. The prototype of the efficient pick-up device for automatic transplanting: (1) plug seedling; (2) pick-up manipulator; (3) feeding device; (4) loosening device; (5) pneumatic cable; (6) control system.

(**a**) Success in picking up a row of seedlings



(**b**) Failure to pick up plug seedlings



(**c**) Seedling morphology of automatic picking

Figure 14. The operation process of the efficient pick-up device for automatic transplanting.