



A whole row automatic pick-up device using air force to blow out vegetable plug seedlings

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Abstract

Aim of study: To develop a whole row automatic pick-up device using air force to blow out plug seedlings, to avoid the damage to seedlings that the current way of seedling picking by needle insertion induces.

Area of study: Jiangsu Province, China.

Material and methods: We designed a pick-up device which mainly consists of a seedling transporting device, a seedling air loosening device, a seedling clamping device and an automatic control system. The damage rate of seedling was significantly reduced and the success rate of seedling picking was increased by using the new seedling air loosening method and the new designed end-effectors. A prototype of the new pick-up device was produced according to the calculation results, and the performance tests were arranged under actual production conditions in an indoor laboratory.

Main Results: The calculation showed that when the diameter of the blowhole in air nozzle is 3.5 mm, and the air pressure is between 0.146 MPa and 0.315 MPa, the seedlings can be blown out successfully. Besides, the clamping strain test showed that the new designed end-effector can meet the requirements of seedling picking. The orthogonal test showed that both the air pressure and water content significantly affected the success ratio. The success ratio reached 96.64% when air pressure was 0.4 MPa, water content was 55%-60% and airflow rate was 100%, what meets the current requirements of transplanting.

Research highlights: This research can provide some references for the automatic transplanting technology.

Additional key words: air loosening; end-effector; control system; test.

Authors' contributions: GXM: main design of the device and its testing and analysis. HPM, LHH and JPH: overall conception of the device. YL: partial design of the device and the paper editing. FG: assisted the work.

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Introduction

China has the highest vegetable production and consumption in the world now, with the vegetable planting area of 20 million hectares and an annual output of more than 700 million tons (National Bureau of Statistics of China, 2019). With the decrease of labor force and the increase of labor cost, many kinds of vegetables such as

pepper, tomato and cucumber are transplanted by using the semi-automatic transplanters (Kumar & Raheman, 2011; Zhang *et al.*, 2011), but these semi-automatic transplanters operate at a low speed because the process of seedling transporting and picking still need to be done manually, so we must find some ways to guarantee the high-speed transplanting and low labor using (Zhang *et al.*, 2013).

In order to improve the transplanting efficiency, we must develop automatic pick-up devices to replace the manual work of seedling transporting and picking. As an important part of the transplanter to realize automatic transplanting, the pick-up device should ensure low damage of the plug seedlings during the seedling picking and dropping process, with all the parts operating fast and accurately (Jin *et al.*, 2018). Scholars from all over the world have already developed some high-efficiency automatic pick-up devices (Chen *et al.*, 2014; Thomas & Kumar, 2017; Khadatkhar *et al.*, 2018; Ye *et al.*, 2019), which can really realize automatic seedling picking instead of manual work. Actually, these pick-up devices are mainly composed of end-effectors to realize seedling picking and dropping, as well as some other parts to make sure the end-effectors can reach each working position. As the core of the automatic pick-up device, the end-effectors must ensure the function of successfully seedling picking from the plug tray and seedling dropping into the transplanting cup (Han *et al.*, 2019b). As early as 1990, Ting *et al.* (1990) designed a sliding needle gripper which was adaptable to a wide range of seedling sizes and shapes. Ryu *et al.* (2001) proposed an end-effector comprised of two air cylinders and fingers with a good transplanting performance. In order to adapt to the seedlings growing in China, Han *et al.* (2015) developed a pincette-type end-effector with two fingers and four pins to pick the seedlings following the previous design, and Tong *et al.* (2019) designed a spade end-effector which could complete the seedling picking and reduce the residual substrate in the plug hole.

At present, most seedling picking methods are designed to ensure that the end-effectors can insert into the seedling pot to clamp the seedlings, and the end-effector must break through the adhesion between the seedling pot and the plug tray in order to pick the seedlings out from the plug tray successfully (Han *et al.*, 2013; Ma *et al.*, 2020a). But the inserting and clamping from the end-effector will bring damages to the root system (Liu *et al.*, 2018), and when the clamping force is less than the sum of the gravity of seedling pot with the adhesion between substrate and the plug tray, the seedling pot will be destroyed by the end-effector. To reduce the damage rate of seedling pot, Tong *et al.* (2019) provided a new seedling picking method, which is the end-effector using four shovel shaped pins to clamp the substrate around the seedling pot instead of inserting into the seedling pot. This method can reduce the damage of the seedling pot to a certain extent, but the damage still exists because the pins will also break out the adhesion between substrate and the plug tray during seedling picking. Comparing the loosened seedlings with the unloosened ones during seedling picking, Yang *et al.* (1991) found that the success rate of seedling picking reached 96.3% when using the loosened plug seedlings, but the rate reached 50.9% when using unloosened plug seed-

lings. Based on the idea for seedling picking easily, Ferrari (2018) created a FUTURA automatic transplanter by using a steel needle to push out the plug seedling, which not only improves the efficiency of seedling picking, but also greatly reduces the damage of seedling pot. In order to match the existing end-effector with the seedling push-out device, Gao *et al.* (2017) simulated and analyzed the working process of the steel needle pushing out the plug seedling by using the EDEM software. Actually, the seedling push-out method has high requirements for the packing property of seedlings. If the packing property is poor, the steel needle will directly thrust into the seedling pot and the root-soil structure of the seedling pot will be destroyed. The survey found that the drainage outlet size of some plastic plug trays in China is not uniform, so the steel needle cannot push out the seedling and sometimes destroy the plug tray, and the matching accuracy of steel needle and drainage outlet of the plug tray is also very high.

Xiang *et al.* (2007) developed an experiment of throwing rice seedlings by air force for rice transplanter, the air flow generated by air compressor is used to blow the rice seedling into seedling guide tube during the experiment, and this method is not easy to destroy rice seedlings and the structure is simple compared with the push-out device.

Drawing on the successful experience of the rice transplanter, this was aimed to design an automatic pick-up device using air force to blow out vegetable plug seedlings with some flexible clamping end-effectors picking and dropping seedlings. Besides, a control program was designed to match the actions between the air loosening device and the end-effectors, and an experiment of prototype was implemented to analyze the optimum parameters of the pick-up device.

Material and methods

Design requirements

The following requirements were taken in account when designing the automatic pick-up device:

1. Plastic plug tray had 72 (6×12) holes; the upper and lower caliber of one hole were 40×40 mm and 20×20 mm respectively, and the depth of one hole was 45 mm. Chinese soft plastic plug trays were used (provided by Longji Plastics Co., Taizhou, China).

2. The substrates used in the plug trays were composed of peat, vermiculite and perlite at volume ratio of 3:1:1, the volume ratio of substrates to one hole was 1:1.2, and the moisture content of the substrates was 55-65% (Miao *et al.*, 2013). The seedlings used in the test were 25-30 days old, and the height of the seedlings was from ~100 mm to ~200 mm.

3. The whole row seedling picking method was designed to improve the efficiency of seedling picking and reduce the damage of the seedlings during the working process. As shown in Fig. 1, when the plug tray is in place, the first six seedlings marked F will be picked together with six end-effectors installed in the pick-up device, then the transporting device will move one hole in the transporting direction for another six seedlings (marked S) picking, so the pick-up device can pick one row seedlings during two movements.

4. The end-effector should be vertical to the plug tray when picking seedlings, and the seedlings should be dropped to the seedling cup in the vertical direction. Besides, the end-effector should ensure the integrity of seedlings during the working process.

5. Picking frequency: following the transplanting speed of the transplanter in China, the picking frequency of the pick-up device should not be < 90 plants/min.

Structure and working principle of the pick-up device

According to the requirements mentioned above, the pick-up device was mainly composed of a seedling air loosening device, a seedling clamping device, some seedling cups, an automatic control system, an air compressor and the fixed frame (Fig. 2). A seedling transporting device is needed to feed seedlings to the pick-up device. The seedling air loosening device was installed under the lower surface of the tray baseplate in the seedling transporting device, which was used to blow out the seedlings from the plug tray. The seedling clamping device can move to the predetermined positions with the seedlings outside the plug tray. Finally, the seedling cups accept the seedlings dropped from the seedling clamping device. The frame, assembled from some aluminum profiles, is easy to install and with

high quality. Most of the devices are driven by the air force supplied from the air compressor and stepper motor under the arrangement of the automatic control system.

As shown in Fig. 3, the working process is divided into six parts (a-f) for better explanation. Taking one working cycle as an example:

(1) Before seedling picking, the seedling clamping device ([1]; the same blow) is in the seedling dropping position and the seedling air loosening device [6] is in the initial state (Fig. 3a).

(2) When the seedling transporting device [4] feeds the plug tray [2] to the preset position, the seedling clamping device will flip to the seedling picking position, and the seedling air loosening device will push the air nozzle [5] close to the bottom of the plug tray (Fig. 3b).

(3) After that, the air nozzle will blow out the plug seedling (marked 3) from the plug tray, and the seedling clamping device will clamp the plug seedling at the same time (Fig. 3c).

(4) After seedling picking, the seedling clamping device will flip back to the seedling dropping position, and the air nozzle will turn back to the initial state to prepare for the next seedling picking (Fig. 3d, e).

(5) Finally, the seedling clamping device will drop the seedling in the vertical direction into the seedling cup [8], and that is the end of one cycle (Fig. 3f);

(6) All the devices will repeat this cycle again until all seedlings are taken out from one plug tray, and the plug tray will drop into the tray collection box [7] for reuse.

Seedling transporting device

In order to cooperate with the seedling clamping device and seedling air loosening device, a seedling transporting device was developed in detail following the design requirements, and the function of the seedling

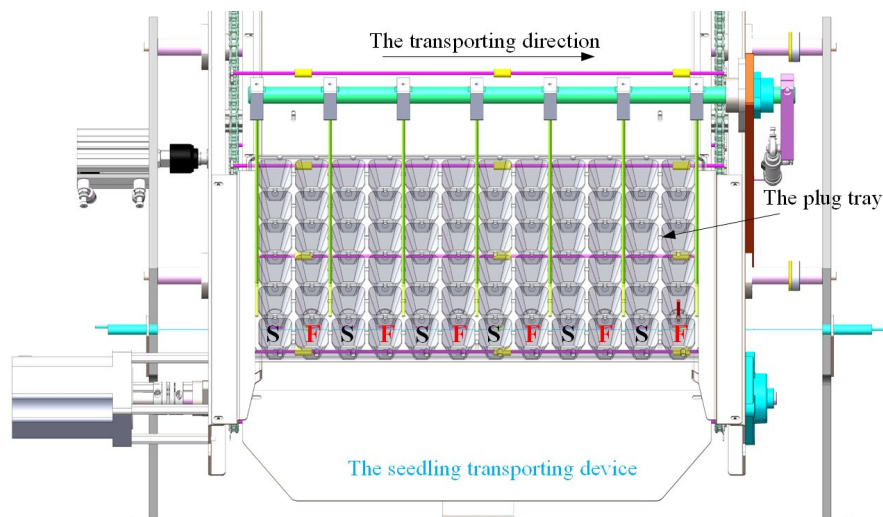


Figure 1. Diagram of the whole row seedling picking method.

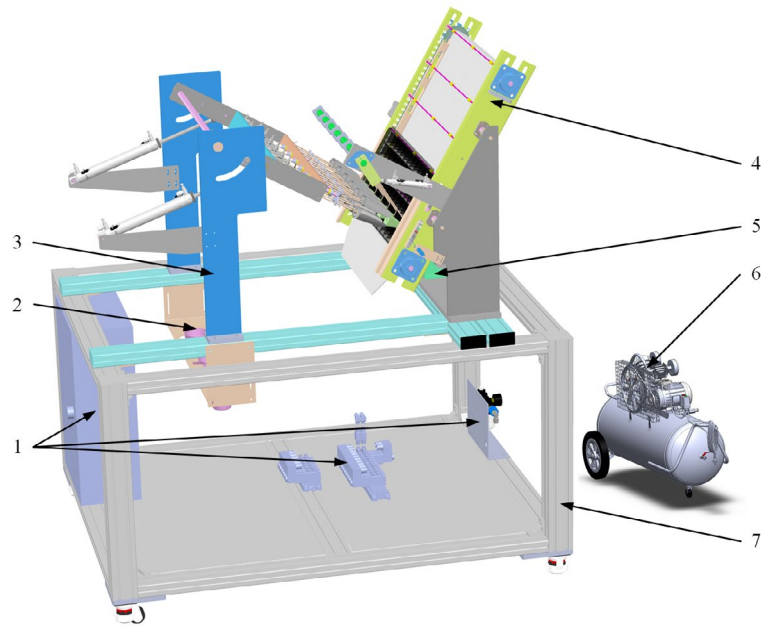


Figure 2. Main structure diagram of the fully automatic pick-up device: 1, automatic control system; 2, seedling cups; 3, seedling clamping device; 4, seedling cups; 5, seedling transporting device; 6, seedling air loosening device; 7, fixed frame; 8, air compressor.

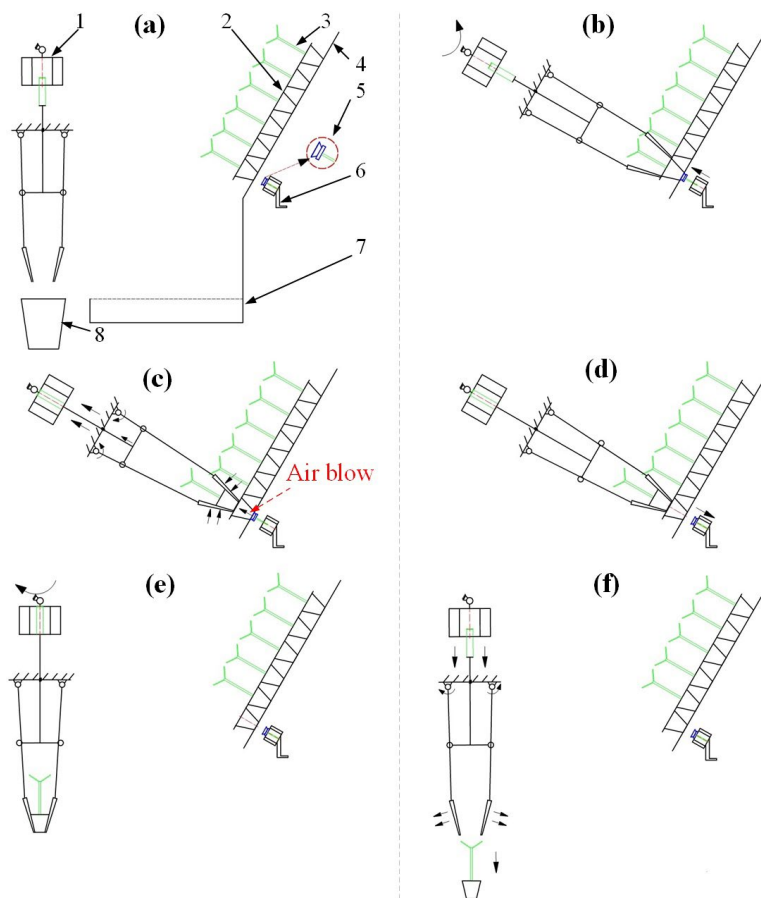


Figure 3. Working principle of the fully automatic pick-up device: 1, seedling clamping device; 2, plug tray; 3, plug seedling; 4, seedling transporting device; 5, air nozzle; 6, seedling air loosening device; 7, tray collection box; 8, seedling cups. The arrows indicate the movement.

transporting device was feeding the plug tray to the required position. As shown in Fig. 4, the seedling transporting device was mainly composed of a chain-type longitudinal transporting device, an air cylinder device for transversal feeding and an automatic control system with some sensors. The seedling transporting device can place two plug trays in the tray baseplate at the same time, and the trays are fixed between two leading tray plates connected with the chains. When the trays are placed into the leading tray rods, the stepper motor drives the chain to rotate, so the device can realize the longitudinal transporting. The supporting tray pipes installed in the leading tray rods are used to better fix the plug tray, so the position accuracy of the plug tray can be guaranteed.

During the first feeding process, the plug tray will move into the pressing tray plate until it reaches the picking position, so the laser beam of the laser sensor will be blocked by the front surface of the tray. Meanwhile, the flip cylinder will drive the pressing tray device to press down the plug tray, and the seedling air loosening device will extend through the air blowing holes to make the air nozzle fit closely with the bottom of the plug hole, then the first six seedlings will be blown out from the plug tray. The pressing tray rods parallel installed in the pressing tray device are designed to press the edge of the plug holes, which not only ensures the enough downforce to the tray, but also avoids the mutual interference between the

end-effectors and the pressing tray rods. Besides, the air blowing holes are designed like an ellipse, and the center of the ellipse is the same as the center of the plug hole, so the position of the plug tray and the seedling air loosening device can be precisely adjusted for better cooperation. As the first six seedlings (half of one row) are picked over, the lateral moving cylinder will drive the device to move to the right in the distance of one hole, so the remaining six seedlings can be picked out. After one row picking, the stepper motor will drive the plug tray to move down the distance of one hole for next picking process, so the seedling picking will be repeated until all seedlings in the plug tray are picked out. Finally, the empty plug tray will drop into the tray collection box, to be fed into the picking position for repeated seedling picking.

Seedling air loosening device

As the core part of the whole device, a seedling air loosening device was designed to blow out the plug seedlings from the plug tray with low damage to the substrate and the root system, which directly affects the performance of the whole device. As shown in Fig. 5, the seedling air loosening device mainly consists of an air blow system and a cylinder, both of them are driven by air force. When the seedling plug tray is fed to the seedling picking position, the flip cylinder in Fig. 4 will extend and drive

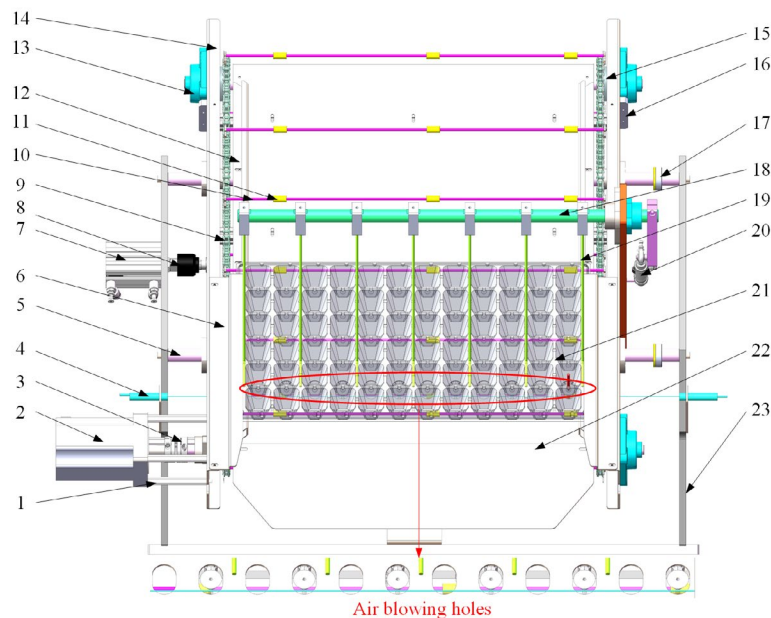


Figure 4. Diagram of the seedling transporting device: 1, hexagonal prism; 2, stepper motor; 3, coupling; 4, laser sensor; 5, sliding rod; 6, pressing tray plate; 7, lateral moving cylinder; 8, floating joint; 9, chain; 10, leading tray rod; 11, supporting tray pipe; 12, leading tray plate; 13, self-aligning bearing; 14, mounting plate; 15, chain wheel; 16, fastening device; 17, limit rubber strip; 18, pressing tray device; 19, pressing tray rod; 20, flip cylinder; 21, plug tray; 22, tray baseplate; 23, frame.

the pressing tray device to press the plug tray so that it will be in close contact with the tray baseplate, then the air cylinder in Fig. 5 will push the air blow system to make the air nozzle closely connected with the bottom of the plug tray, and the center of the air nozzle should be aligned with the center of the plug hole one by one, so the plug seedlings can be blown out successfully by the seedling air loosening device.

The number of air nozzles was designed according to the number of the holes arranged in the plug tray, so the seedling air loosening device can blow out half of one row seedlings at a time, which can ensure the efficiency and the quality of seedling picking at the same time. Actually, it requires a large pressure to blow out the seedlings, so it is necessary to ensure the airtightness of the whole device. In order to achieve this goal, we drilled some through-holes directly on the mounting plate by using laser drilling technology; the air nozzles and intake nozzles with G-thread (GB/T7307-2001) were installed at both ends of through-holes, and all of the G-threads were coated with the liquid state PTFE tape in order to improve the airtightness of the nozzles. Besides, some soft suckers were installed at the front end of the air nozzles, which can fit close to the bottom of the plug tray under the pressure, so this method can effectively prevent air leakage during the process of air blowing.

In addition to ensuring the air tightness of the whole device, the structural form and size of the air nozzle are also important to ensure the plug seedling can be blown out successfully. The investigation shows that most of the drainage outlets in the plug tray were not in the center due to a problem of the injection molding process, but the position of the air nozzles was based on the position

of the drainage outlets in the standard plug tray, so the air nozzles could not be adjusted adaptively during the working process if the drainage outlets were not in the standard position. In order to ensure that the air nozzle could adapt to the drainage outlets at different places on the plug tray and successfully blow out the plug seedlings, it was necessary to select a reasonable diameter of the blowhole in the air nozzle.

As shown in Fig. 6, D is the diameter of the standard drainage outlet, and D_0 is the actual diameter of the blowhole we want to work out. It is well known that PVC plastic plug trays are one-time formed by the injection molding process, and the drainage outlets in the tray are formed by the whole row stamping process, so the diameters of all drainage outlets are the same in standard, but the positions of the drainage outlets will be different (marked 3 in Fig. 6) because of the errors existing during the manufacturing process. In order to ensure the accuracy value of D_0 , we randomly selected some standard 72-hole plug trays and measured the length of m (Fig. 5) by using a simple random sampling method. First, we used two crosshair laser localizers to mark the center of the standard drainage outlet and the possible drainage outlet in the same tray hole respectively; then, we selected the high-accuracy Total Station to measure the length between the two crosshairs; finally, we substituted the measured value into the Eq. (1):

$$\begin{cases} D_0 = 2 \times \left(\frac{D}{2} - m \right) \\ m = \max(m_1, m_2, \dots, m_i) \end{cases} \quad (1)$$

where m_i is the distance between the center of the standard and the possible drainage outlet of the i -th tray hole.

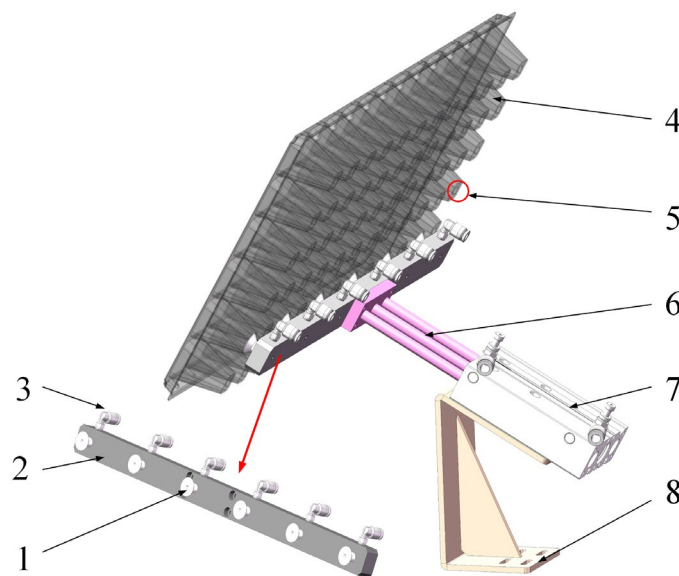


Figure 5. Structure diagram of the seedling air loosening device: 1, air nozzle; 2, mounting plate; 3, intake nozzle; 4, plug tray; 5, drainage outlet; 6, piston rod; 7, air cylinder; 8, frame.

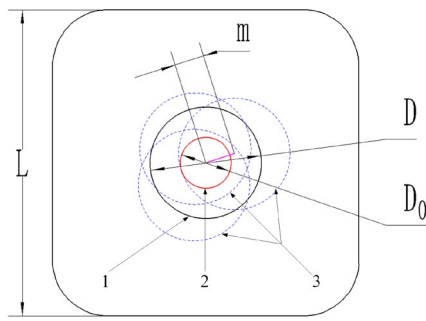


Figure 6. Establishment of the blowhole's diameter: 1, standard position of the drainage outlet; 2, position of the blowhole; 3, possible positions of the drainage outlet. L , width of the plug hole's bottom; D , diameter of the standard drainage outlet; D_0 , diameter of the blowhole; m , distance between the center of the standard and possible drainage outlet (units: mm).

According to the measurement results, $D=7$ mm and $m=1.73$ mm, so the blowhole diameter $D_0=3.54$ mm. In order to select the proper size of the air nozzle, the diameter of the blowhole was regulated to 3.5 mm.

Compared with the end-effectors inserting and clamping the seedlings out from the plug tray (Han *et al.*, 2013), our device uses the air force to blow out the seedlings. No matter which method is used to pick the seedlings out from the tray, it is necessary to let the seedlings get rid of the adhesion of the plug tray, so we must calculate the air pressure acting on the bottom of the seedling to ensure that there is enough pressure to blow the seedling out. According to theory of subsonic free jet (Zhao & Jiang, 1998), we simplified the airflow field during the process of air blowing as shown in Fig. 7. At present, the substrate of seedling is mainly composed of peat, perlite

and vermiculite in a certain proportion, so the adhesion is formed by the mixture of substrate, root system and the wall of the tray (Miao *et al.*, 2013). Besides, it takes a lot of force to blow out the seedling, but the force should not be too large to destroy the seedling, so the air force must meet the Eq. (2):

$$\begin{cases} F_S = G + F_N \\ F_S < P_0 S < F_B \end{cases} \quad (2)$$

where F_S is the force required to blow out the seedling, N; G , is the gravity of seedling, N; F_N , is the adhesion between seedling and tray, N; F_B is the critical force of seedling destroyed, N; P_0 is the jet pressure at the air nozzle, MPa; and S is the actual area of jet action on the bottom of seedling, m^2 .

In order to ensure the stability and pressure demand of the air system, we chose 6 mm and 8 mm air pipes to connect air compressor and pneumatic components; these air pipes are much larger than the diameter of the blowhole, so when the airflow passes through the blowhole, it will form a contracted flow effect (Han *et al.*, 2004), the air nozzle is similar to a throttle valve at this time (Fig. 7a). According to Bernoulli equation, we can get:

$$\begin{cases} \xi = \left(\frac{S_1}{S_0} - 1 \right)^2 \\ v_0^2 - v^2 = \xi \left(\frac{v_0 + v}{2} \right)^2 \\ P_0 = P - \frac{\xi \rho v_0^2}{2} \end{cases} \quad (3)$$

where ξ is coefficient of flow resistance; P and P_0 are the pressure at the inlet and outlet respectively, MPa; v and v_0 are the flow velocity at the inlet and outlet respectively,

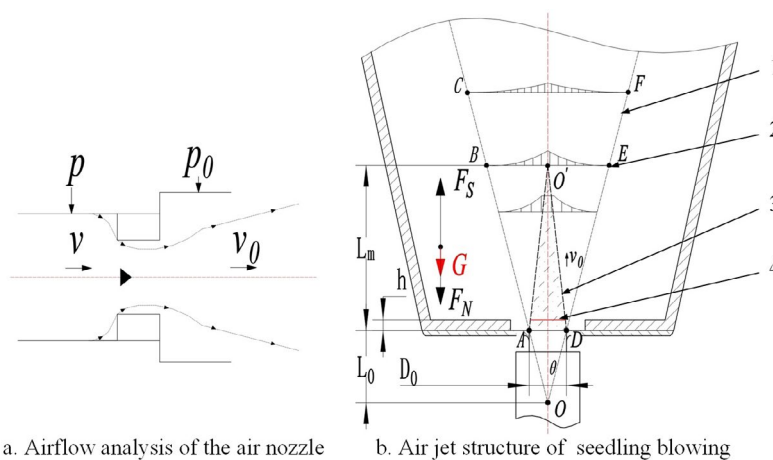


Figure 7. Simplified airflow structure during the blowing process: 1, jet boundary layer (DEF); 2, transitional surface (BO'E); 3, jet core area (AO'D); 4, actual area of jet action on the bottom of seedling. O , jet pole; D_0 , diameter of the blowhole, mm; v_0 , jet velocity, m/s; h , thickness of the tray wall, mm; L_0 , depth of the jet pole, mm; L_m , length of core area, mm; G , gravity of seedling, N; F_N , adhesion between seedling and tray, N; F_S , force required to blow out the seedling, N.

m/s; S_0 is the surface area of the blowhole, m^2 ; S_1 is the surface area of the drainage outlet, m^2 ; and ρ is the density of air flow, kg/m^3 .

According to the jet theory, jet core area (AO'D) marked in Fig. 7b is the main effective area of air flow, and the velocity in this area is the same as v_0 , so we just need to calculate the jet force acted on the seedling of this area. Because of a certain thickness of the tray (marked h in Fig. 7b), the actual area which the jet acted on the bottom of the seedlings is the line marked 4 in Fig. 7b, so we can easily get the actual action area as

$$\begin{cases} L_0 = \frac{0.294D_0}{2\alpha} \\ r = \left(1 + \frac{h}{L_0}\right) \times \frac{D_0}{2} \\ S = \pi r^2 \end{cases} \quad (4)$$

where r is the radius of the actual action area of the jet, mm; α is the turbulence coefficient, and the air nozzle is a cylindrical tube, so $\alpha=0.076$.

Han *et al.* (2015) and Wang *et al.* (2016) showed that the adhesion force F_N can be approximately equal to the detaching force F_D which could separate the seedling from the tray, and Miao *et al.* (2013) proposed that the average detaching force of the cucumber seedling which grew in the 72-hole plug tray is 1.44 N. Besides, we randomly selected a group of cucumber seedlings and weighed them, so the average value of gravity was 0.21 N, and we also measured the thickness of the plug tray, so $h=0.08$ mm. Han *et al.* (2019a) got the critical force of seedling destroyed with the help of the puncture test commonly used in food science, so $F_B = (3.08 \pm 0.56)$ N. Putting all the data together with the diameter of the blowhole into the Eqs. (2), (3) and (4), the theoretical jet pressure (P_0) at the air nozzle was between 0.146 and 0.315 MPa. According to the established jet pressure, we can also find out the required outlet pressure of the air compressor and the solenoid valves.

Seedling clamping device

The function of the seedling clamping device is to clamp the seedlings blown out from the seedling air loosening device, transporting them into the seedling dropping position and then dropping them into the transplanting device. As shown in Fig. 8, the seedling clamping device mainly consists of whole row end-effectors, pushing cylinders, flip cylinders and the frame, and the end-effectors are the core components of the seedling clamping device which will influence the quality of seedling picking and dropping, so it is important to design and calculate the parameters of the end-effectors in detail.

Compared with the end-effectors developed by Han *et al.* (2013) and Tong *et al.* (2019), our end-effector will pick the seedling by clamping the surface around the seedling body, which can avoid the disturbance of the root system and the damage of the seedling body caused by the insertion of the needles.

The working principle of the end-effector is shown in Fig. 9. At first, the end-effector is in the initial state, when a work cycle starts, the seedling air loosening device blows out the seedling from the plug tray (Fig. 9a). As the seedling moves into the range of the grippers, the pushing cylinder gets the signal so that the pull rod will retract and drive the pull plate to move upward, and the grippers contract inward to clamp the seedlings (Fig. 9b). Then the end-effector is driven by the flip cylinder and quickly moves into the dropping position; after that, the cylinder drives the pull rod to extend, so the gripper opens and drops the seedlings (Fig. 9c).

In order to ensure the success rate of seedling picking, it is important to design and optimize the parameters of the end-effector. The simplified designed structure of the end-effector is shown in Fig. 10. By analyzing the structure diagram, we can get the distance between installation points of two picking needles as:

$$\begin{cases} L = L_2 + 2 \times S \times \sin \alpha_1 \\ L = L_3 + 2 \times S \times \sin \alpha_2 \end{cases} \quad (5)$$

And then we can get the length of the pull plate as:

$$\begin{cases} L_1 = L - 2(S - S_1) \sin \alpha_1 \\ L_1 = L - 2(S - S_2) \sin \alpha_2 \\ H = S_2 \cos \alpha_2 - S_1 \cos \alpha_1 \end{cases} \quad (6)$$

Actually, the main parameters of the end-effectors are mostly determined by the seedling sizes and features. According to Ma *et al.* (2020b), the upper side length $a=40$ mm, the lower side length $b=20$ mm, and the cone angle of one plug hole $\beta=22.5^\circ$. Besides, the height of plug seedlings suitable for transplanting is generally about 100-200 mm and, in order to successfully clamp the seedlings, we should ensure seedling clamping exceed the biological yield point (compression quantity: 3.46 mm) to provide enough clamping force (Han *et al.*, 2013). So we can easily get the restraint conditions as:

$$\begin{cases} (b - 3.46)mm < L_3 < L_2 < (a + 3)mm \\ \alpha_1 > \arcsin \frac{L - (a + 3)}{2S} \\ \alpha_2 > \frac{\beta}{2} \\ S_2 \cos \alpha_2 > S_1 \cos \alpha_1 \geq 170mm \end{cases} \quad (7)$$

As shown in Table 1, combining Eqs. (5), (6) and (7), we can get the parameters of the key components in the end-effector, and we designed the end-effector

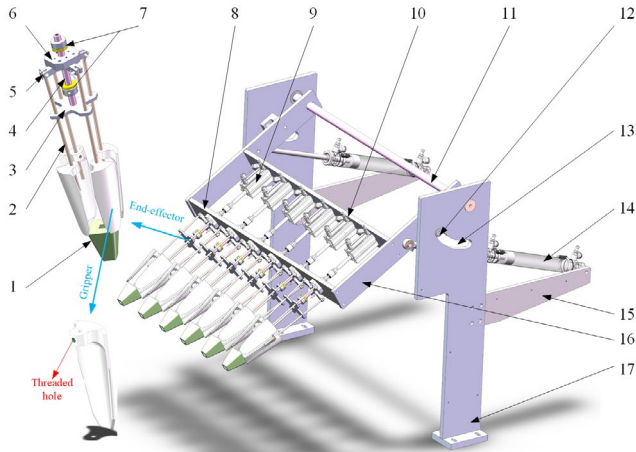


Figure 8. Structure diagram of the seedling clamping device: 1, plug seedling; 2, picking needle; 3, pull plate; 4, pull rod; 5, swing shaft; 6, fixed plate; 7, limit block; 8, end-effector assembling plate; 9, pushing cylinder; 10, pushing cylinder assembling plate; 11, rotation axis; 12, roller; 13, chute; 14, flip cylinder; 15, flip cylinder assembling plate; 16, flip plate; 17, frame.

(Fig. 8) in detail according to the parameters. We used the 3D printing technology to build the grippers, which can better protect the seedlings and ensure the accuracy of the grippers. Each gripper has one threaded hole, so we can fasten the gripper and the needle by screws, and also adjust the height of the grippers flexibly according to the demand. Besides, we also installed some limit blocks (marked 7 in Fig. 8) in the pull rod, so the end-effector can pick the seedlings of different sizes by adjusting the position of the limit blocks.

Automatic control system

As the most important part in the pick-up device, the automatic control system manages and coordinates the operation of various parts, to ensure the automation and the normal operation of the device equipped with both

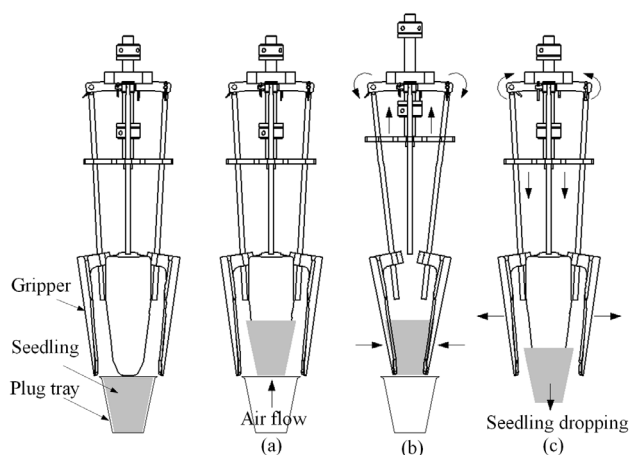


Figure 9. Principle diagram of the end-effector.

electromechanical and pneumatic units. As shown in Fig. 11, the automatic control system is composed of the IPC (industrial computer), a mobile workstation, some sensors, some solenoid valves and some other executive elements. As the center of the whole system, the IPC consists of some relays, switches and some other components, it receives and transmits signals from the sensors, switches and some judgement parts, so as to control the executive elements to complete the specified actions. The photoelectric sensor is used to monitor the position signal of the plug tray so as to control the rotation and stop the stepping motor. Each pneumatic element is equipped with a solenoid valve and each air circuit has a throttle valve, they are all connected to relays to realize precise control. Following other pick-up devices, we installed magnetic switches on each cylinder, so the system could precisely control the extension and retraction position of the cylinder. Besides, the two flip cylinders were connected to the same solenoid valve, so the two flip cylinders could realize synchronous operations. A mobile workstation was needed so we could easily monitor the real-time running status of the system, and we could also set some key parameters such as picking speed, flow rate, start & off, and so on. Besides, the program was edited in Visual Studio 2018 to run in the workstation, and we also added analog quantity in the program to display the real-time flow rate of the air nozzle from the digital display flowmeter, so we could ensure the accuracy of the seedling loosening.

As shown in Fig. 12, the whole pneumatic system was edited by FluidSIM-P 3.6. All double-acting cylinders were connected with the 2-position, 5-way solenoid valves (SV_1 - SV_{10}); all air nozzles were connected with the 2-position, 3-way solenoid valves (SV_{11} - SV_{16}); and all solenoid valves were controlled by the relays. The flip cylinders C_1 and C_2 were connected to the same solenoid valve, used to swing the end-effectors to the seedling picking or dropping position; the cylinder C_3 was used to move the seedling transporting device left and right; C_4 was used to pressure the plug tray during the seedling picking process; C_5 to push the air nozzles to the blowing position, and C_6 - C_{11} to drive the end-effectors opening and closing. The air nozzles N_1 - N_6 were used to blow out the seedlings from the plug tray, and each air nozzle was connected with a digital display flowmeter (P_1 - P_6) to monitor the real-time blowing pressure. Each air path was connected with a throttle valve, so the whole system could adjust different pressures and flows according to different recommendations.

Performance test

According to these data, a prototype of the automatic pick-up device was produced, and an indoor experiment was arranged in order to test the working performance of

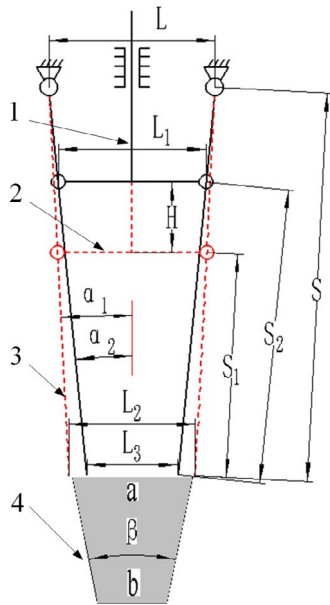


Figure 10. Simplified scheme of the end-effector: 1, pull rod; 2, pull plate; 3, picking pin; 4, seedling. L , distance between installation points of two picking pins, mm; L_1 , length of the pull plate, mm; L_2, L_3 , distance between the pin tips when the seedling is not clamped and clamped respectively, mm; S , length of the picking pin, mm; S_1, S_2 , distance between the pin tips and the pull plate when the seedling is not clamped and clamped respectively, mm; H , distance between the pull plate under the two different states; α_1, α_2 , angle between pin and vertical direction when the seedling is not clamped and clamped respectively, °; β , cone angle of one plug hole, °; a, b , upper and the lower side length of the seedling respectively, mm.

the pick-up device in Jiangsu university, Zhenjiang, China. High quality 72-hole PS plug trays were selected to cultivate tomato cv. Zhefen 202 (provided by Institute of Horticulture, Zhejiang Academy of Agricultural Sciences, Zhejiang, China) seedlings under the design requirements.

The new end-effector was designed according to the actual parameters of the seedling, so it can meet the requirements of seedling picking. Actually, the end-effector should not only ensure that the seedling can be picked out, but also avoid the damage of the seedling, so we used the dynamic strain measuring system (Fig. 13a) to test the mechanical properties of the end-effector in order to ensure its reliability. In order to eliminate

Table 1. The parameters of the end-effector

Components	Value	Components	Value
L , mm	65	S_1 , mm	175
L_1 , mm	55.5	S_2 , mm	205
L_2 , mm	44	H , mm	26.6
L_3 , mm	20	α_1 , °	5.3
S , mm	226	α_2 , °	11.5

the effect of asymmetry of grippers, the two strain gauges were connected to the strain gauge through a half bridge circuit (Fig. 13b), and two strain gauges were symmetrically arranged on the inside and outside of a single gripper (Fig. 13c). After connecting each instrument circuit, we calibrated the dynamic strain measuring system following Wang & Hu. (2020) (Fig. 13d), and then tested the stress of the seedling during the process of seedling clamping.

Previous studies have shown that water content affects the adhesion between seedlings and plug tray (Ting *et al.*, 1990; Miao *et al.*, 2013), so we tested the effect of the seedling air loosening at different water contents: 50-55%, 55-60%, 60-65%. The air pressure was also the key to the success rate of seedling picking, according to the above calculation; the theoretical air pressure required was between 0.146 MPa and 0.315 MPa, so three levels (0.3 MPa, 0.4 MPa and 0.5 MPa) were selected for the air pressure considering the pressure loss in the pneumatic circuit. Besides, the value of airflow also affects the success rate of seedling picking, so we installed a throttle valve in each circuit to adjust the airflow, and we selected 50%, 75% and 100% airflows. In order to ensure that the seedlings are successfully blown out from the tray, we set the solenoid valves (SV_{11} - SV_{16}) with a delay of 0.2 s, and we selected a 0.8 MPa air compressor to ensure the stability of airflow. The picking frequency was set at 120 plants/min.

As shown in Table 2, A, B and C were determined as the coding values of air pressure, airflow rate and water content, respectively. An $L^9(3^3)$ orthogonal table was selected in the orthogonal experiments, and each group selected one tray (72 seedlings), taking the average value as the result data of each group, the seedling picking test is shown in Fig. 14. The experimental results were analyzed by SPSS 23.0 with general linear model.

Ryu *et al.* (2001) indicated that the seedlings are not able to survive when their damage degree was $> 1/4$, so we defined the seedling damage degree (S_d) as:

$$S_d = \frac{W_{ms}}{W_{cs} + W_{ms}} \quad (8)$$

where W_{cs} is the weight of the seedling after blowing out, g; and W_{ms} is the weight of the substrate remained in the tray and scattered outside, g.

Taking these factors into consideration, the success ratio of seedling picking (R_{sp}) was defined as

$$R_{SP} = \frac{N_{ts} - N_{ms} - N_{ds} - N_{fs}}{N_{ts} - N_{ms}} \times 100\% \quad (9)$$

where N_{ts} is the number of seedlings in total, N_{ms} is the number of missing seedlings, N_{ds} is the seedlings with stem and leaf injury, and N_{fs} is the seedlings with more than 1/4 damage.

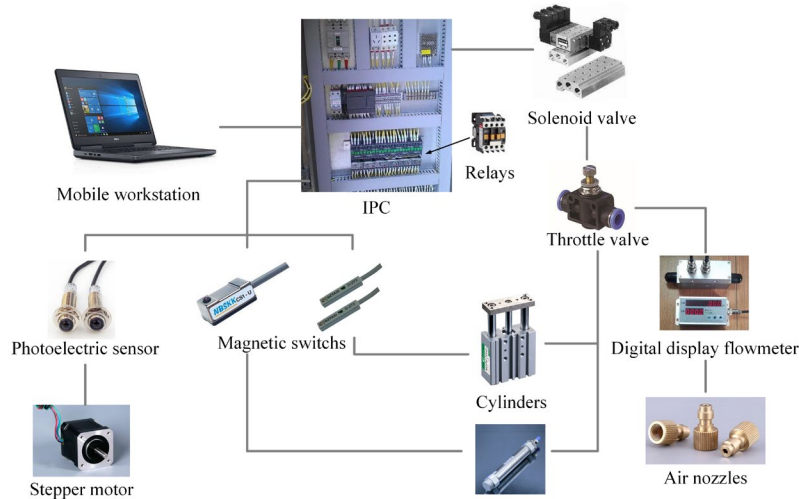


Figure 11. Structure of the automatic control system.

Results and discussion

The strain gauges were attached to the grippers, and we fixed one gripper to calibrate the strain gauge (Fig. 13d), then we returned the strain instrument to measure the calibration value. We applied forces to the gripper, increasing 1 N each time, from 0 N to 8 N, then we used the least square method to calculate linear fitting of the data. The fitting results (Fig. 15a), show that the linear relationship between the input voltage (mV) and the applied force (N) was $y=56.876x-0.954$.

After the strain gauge was calibrated, we installed the grippers with strain gauges in the end-effector, and started the seedling clamping device to clamp the seedling,

the input voltage was collected all the time during this period until the grippers were completely closed (Fig. 15b). After repeated clamping for three times, we got the average input voltage: 158.906 mV, so the corresponding compressive force on the seedling was 2.805 N. Ren *et al.* (2020) proposed that tomato seedlings substrate will start to damage when the pressure reaches 3.15 N, so the new designed end-effector can meet the needs of automatic seedling picking.

According to the experiments, the results of the performance test for the pick-up device, results of range analysis, and results of variance analysis are shown in Tables 3, 4 and 5 respectively. As shown in Table 4, the influence on the success ratio ranked $A > C > B$, and when air pressure

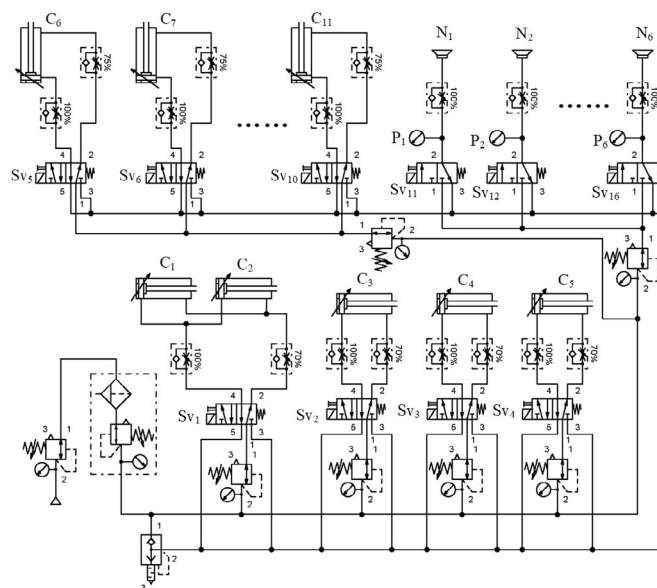


Figure 12. Pneumatic schematic diagram of the whole pick-up device. C_1 - C_{11} , cylinders in the pneumatic system; SV_1 - SV_{16} , solenoid valves in the pneumatic system; N_1 - N_6 , air nozzles in the seedling air loosening device; P_1 - P_6 , digital display flowmeters for air nozzles.

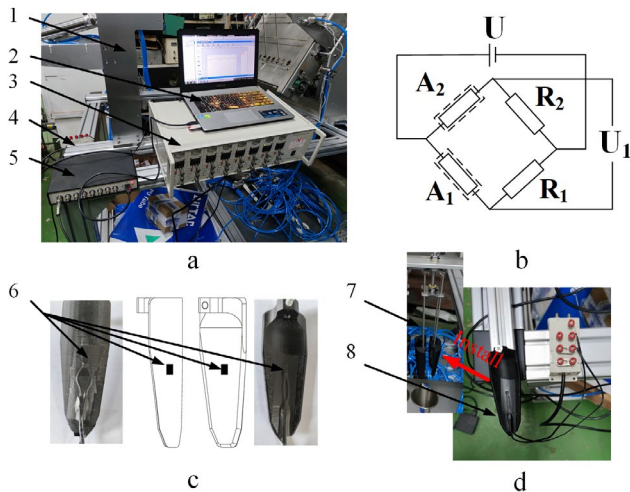


Figure 13. The clamping forces tests during the seedling picking: 1, the seedling clamping device; 2, mobile workstation; 3, dynamic resistance strain instrument (BZ2204A); 4, bridge box; 5, data acquisition and analysis system (BZ7201-USB); 6, strain gauge (BFH120-5AA); 7, end-effector; 8, gripper. U, voltage of bridge box; U₁, voltage of measured clamping force.

was 0.3 MPa, airflow rate 100%, and water content between 55% and 60%, the highest success rate of seedling picking was obtained. Table 5 shows that the success ratio of seedling picking was extremely significantly affected by air pressure ($p < 0.01$), significantly affected by the water content ($0.01 < p < 0.05$), but not significantly affected by the airflow rate ($p > 0.05$).

According to the range analysis, the air pressure extremely significantly affected the success ratio of the pick-up device by adopting the seedling air loosening method, and the success ratio could reach 94.9% when air pressure was 0.4 MPa. Although the calculated air pressure was between 0.146 MPa and 0.315 MPa, the success ratio sharp declined to 87.49% when air pressure was 0.3 MPa. The reason is that some of the seedlings have advanced root systems, so the adhesion between these seedlings and tray is too strong, and there is a certain degree of loss in the air circuit, thus the air pressure is too low to blow out these seedlings from the tray, bringing out the low success ratio. When air pressure reached 0.5 MPa, almost all the seedlings could be blown out from the tray, but some seedlings with lighter weight will collide with the end-effector after the blowing because of the overpressure from the air loo-

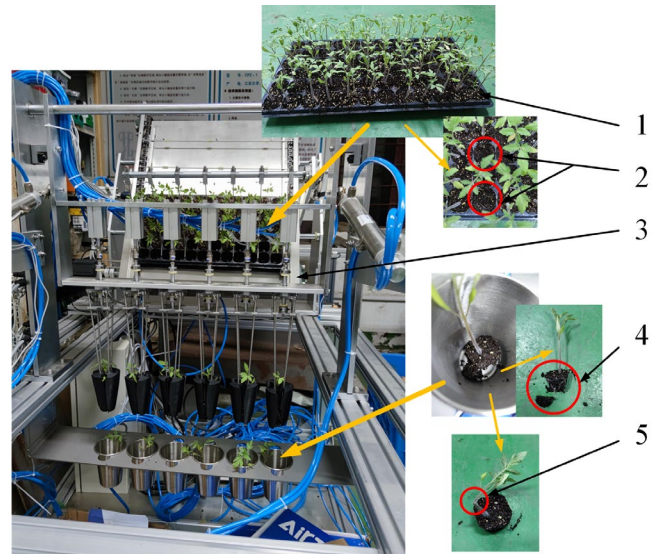


Figure 14. Seedling picking test of the pick-up device: 1, tomato seedlings; 2, missing seedling; 3, pick-up device; 4, damage seedling; 5, stem and leaf injury seedling.

sening device, which will destroy the substrate of the seedling and sometimes break off the item and the leaf of the seedling. Besides, although a small part of the seedlings with poor root systems can be blown out, too much airflow will blow away part of their substrates, which will also affect the success ratio. Because of the particularity of air blowing, it is important to choose a suitable air pressure to ensure the success ratio of seedling picking.

Previous studies showed that water content will affect the strength of the seedling substrate, and also affect the adhesion between seedlings and plug tray (Miao *et al.*, 2013; Han *et al.*, 2015). The test showed that the best success ratio (92.81%) was found when the water content was 55-60%. When the water content was 60%-65%, the success ratio declined to 89.9%, and the seedlings maintained relatively integrity. Yang *et al.* (1991) proposed that proper water content could reduce the adhesion between seedlings and tray; our experiment showed that when the water content was $> 60\%$, the success ratio declined because the adhesion continued increasing. But when the water content was 50%-55%, the success ratio was 88.27%; the reason may be that the substrate is loose under this water content, especially when the water content is close to or even less than 50%, so the substrate

Table 2. Factors and levels of the orthogonal optimum tests

Level	Factors		
	A: Air pressure (MPa)	B: Airflow rate (%)	C: Water content (%)
1	0.3	50	50-55
2	0.4	75	55-60
3	0.5	100	60-65

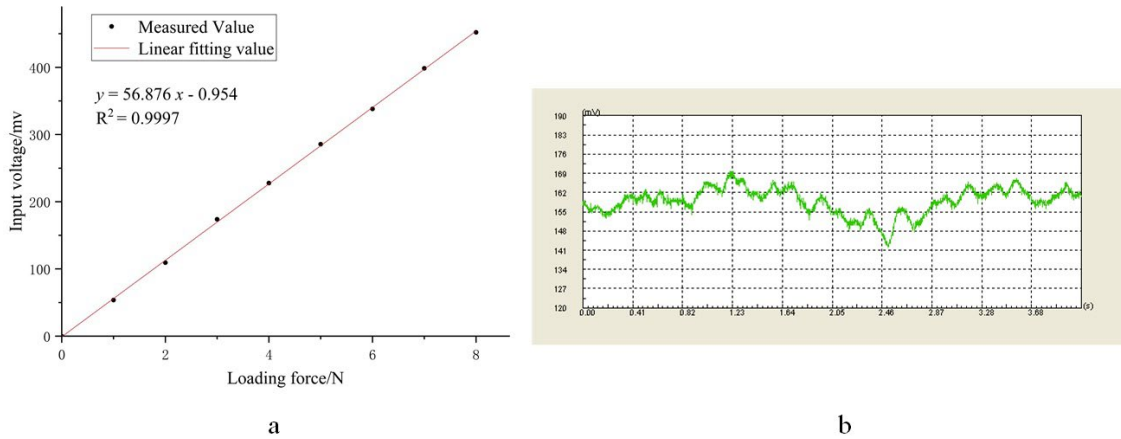


Figure 15. Measurement of mechanical performance of the new designed end-effector: (a) Calibration of the strain system, (b) Input voltage with gripper completely closed.

Table 3. Results of the optimum orthogonal tests

Test No.	Factors			Success ratio (%)
	A	B	C	
1	1 (0.3 MPa)	1 (50%)	1 (50%-55%)	84.11
2	1	2 (75%)	2 (55%-60%)	89.92
3	1	3 (100%)	3 (60%-65%)	88.43
4	2 (0.4 MPa)	1	2	96.39
5	2	2	3	93.65
6	2	3	1	94.67
7	3 (0.5 MPa)	1	3	87.63
8	3	2	1	86.03
9	3	3	2	92.13

Table 4. Range analysis for the orthogonal tests

Factors ^[a]	A	B	C
K_1	87.49	89.38	88.27
K_2	94.90	89.87	92.81
K_3	88.60	91.74	89.90
Maximum	94.90	91.74	92.81
Minimum	87.49	89.38	88.27
Range R	7.41	2.36	4.54
Optimal level	A ₂	B ₃	C ₂

^[a] K_i is the average of all experimental results with the corresponding level i under each factor, and R is the maximum value of K_i minus minimum under each factor.

will be broken easily by the airflow, although the seedling can be blown out under this water content, the value of transplanting is greatly reduced. The substrate is mainly composed of peat, vermiculite and perlite (Miao *et al.*, 2013), then the water content will significantly affect the physical properties of the substrate, so it is im-

portant to control the water content of the seedlings in a reasonable range.

Besides, the effect of the airflow rate on the success ratio is in a rising tendency on the whole, and the success rate reached 91.74% when the airflow rate was 100%. During the experiments, it was found that the time of air

Table 5. Variance analysis for the orthogonal tests

Factor	Sum of squares (<i>S</i>)	Freedom (<i>f</i>)	Mean square (\bar{S})	<i>F</i> value	<i>p</i> value	Significant level ^[a]
A: Air pressure	96.01	2	48.01	105.03	0.009	**
B: Airflow rate	9.36	2	4.68	10.24	0.089	
C: Water content	31.78	2	15.89	34.76	0.028	*
Deviation	0.91	2	0.46			
Sum	138.07					

^[a] **: $p < 0.01$: extremely significant effect; *: $0.01 < p < 0.05$: significant effect.

blowing was longer with the increase of the airflow rate, so full opening of throttle valve will bring higher success rate of seedling picking in the process of air blowing.

The parameters of the pick-up device were adjusted according to the results of the optimal combination from the orthogonal tests, then the performance of the seedling pick-up device was tested and verified. The final results are shown in Table 6. The tests showed that the average success ratio of the new pick-up device was 96.64%, which proves the practicability of the new designed pick-up device, and the air loosening method was also proved. Actually, the correctness of the four-claw end-effectors used in most pick-up devices have been proved in previous studies (Yang *et al.*, 1991; Han *et al.*, 2013; Tong *et al.*, 2019), but the way of inserting the substrate to pick the seedlings will eventually cause some damage to the seedlings, so we improved the end-effectors on the basis of these previous studies which will pick the seedling by clamping the surface around the seedling body. With the cooperation of the new designed end-effectors and the air loosening method, the pick-up device could reduce the damage rate of the seedlings and improve the success rate of seedling picking while realizing high-speed working. Besides, we only used 72-hole plug trays in our paper, but the pick-up device could also pick seedlings from 50-hole or 128-hole plug trays by changing the number of the end-effectors, and the auto-control system will also match with different plug trays. For the particularity of pneumatic driving mode, we installed a throttle valve in each individual pneumatic path, so we can adjust the airflow independently under different requirements.

Although the success ratio was greatly proved by the pick-up device, the phenomenon of seedling missing and damage still existed during the tests. For example, the root system will not completely combine with the substrate if the tray hole cannot be filled in proportion with the substrates; these kind of seedlings will be easily damaged during seedling picking, so it is important to guarantee the quality of seedling raising, and we must carefully select the seeds before seedling raising in order to avoid seedling missing. Besides, Han *et al.* (2013) pointed out that the height of the seedlings must be controlled because of the limit by the end-effectors, so it was very necessary to cultivate short seedlings with good quality. To solve these problems, we should add a seedling detection device before seedling picking to ensure the success ratio of the pick-up device.

In conclusion, a whole row automatic pick-up device for vegetable plug seedlings was developed based on the current demand of vegetable production in China. The device, with seedling air loosening method, combines mechatronics with pneumatics system, which can reduce the damage rate of seedlings while realizing automatic high-speed seedling picking and dropping. As a new pick-up device, the prototype was produced, and the performance tests were conducted under actual production conditions. The test results showed that the success ratio of seedling picking could exceed 95%, and the picking and dropping efficiency could well meet the demand of automatic transplanting. It is still necessary to improve the quality of seedling raising in the future, so that the pick-up device will ensure a higher success ratio.

Table 6. Results of performance tests

Test No.	No. of total seedlings	No. of missing seedlings	No. of stem and leaf injury	No. of damaged seedlings	Success ratio (%)
1	144	5	0	4	97.12
2	144	3	2	3	96.45
3	144	7	1	4	96.35
Average value	144	5	1	3.7	96.64

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