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Optimal design and experimental verification of a four-claw seedling pick-up mechanism using the hybrid PSO-SA algorithm

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Abstract

Aim of study: To develop a novel four-claw seedling pick-up mechanism to integrate penetration and clamping into one process, realizing picking up seedlings stably and efficiently.

Material and methods: A brushless DC servo motor characterized by small size, large torque, and high control precision was adopted to realize precise control for speed and clamping force through control algorithms. An optimization model was derived according to the requirements of picking up seedlings. The parameter optimization of the seedling pick-up mechanism is a complex multi-parameter and nonlinear optimization problem. The hybrid PSO-SA algorithm was used to solve the model, and the optimal parameters of the mechanism were obtained.

Main results: The dynamic simulation was conducted, and the results showed that the optimized mechanism could meet the trajectory, acceleration, and clamping force requirement for picking up seedlings. The performance tests showed that the success ratio in picking up seedlings reached 84.46%, indicating the feasibility of the four-claw seedling pick-up mechanism for automatic transplanting machines.

Research highlights: The four-claw seedling pick-up mechanism can be used in the automatic transplanting machine. Additionally, the hybrid PSO-SA algorithm can achieve promising results in solving the optimization problem of the seedling pick-up mechanism.

Additional key words: optimization; seedling pick-up trajectory; evolutionary algorithms; plug seedlings.

Abbreviations used: DC (direct current); PSO (particle swarm optimization); SA (isimulated annealing).

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Introduction

Seedling transplanting technology of vegetables can effectively improve the survival rate of seedlings, shortening the growth period of vegetables (Feng *et al*., 2020). Currently, more than 60% of the vegetables in China are planted by the seedling transplanting method (He *et al*., 2018; Xia *et al*., 2019). Traditional seedling transplanting is labor-intensive and partly inefficient (Jin *et al*., 2020), making it challenging to apply to large-scale production. The vegetable transplanter provides a means to solve these problems, which is of great significance to developing agricultural mechanization (Vivek *et al*., 2017). However, most transplanters in China are semi-automatic, needing laborers to pick and transport seedlings into the machine (Han, 2014). Therefore, there is an urgent demand for an automatic transplanter.

As an essential component of the automatic transplanter, the seedling pick-up mechanism can greatly improve the efficiency and quality of transplanting. During the past few years, many attempts have been made to develop seedling pick-up devices, and significant progress has been made. The existing seedling pick-up devices for tomato seedlings can be divided into three types: push-out, gripper, and combined. Xu *et al*. (2016) developed a push-out type seedling picking-up device. The seedling is pushed out by the push rod and delivered to the transplanting unit by the seedling feeding mechanism. Test results indicate that the success rate of the seedling pick-up was over 95%. A seedling pick-up device designed by Yang *et al*. (2013) can push the seedling to the transport unit and then transfer it to the casting potted-seedling unit. This push-out type seedling pick-up device is simple in structure, but it requires the high accuracy of the control system.

Ting *et al*. (1990) developed a sliding-needle gripper consisting of a robot wrist, gripper, and a sensor. The gripper can extract the seedling from a plug tray and transport it to the growing flat. Choi *et al*. (2002a) designed a new seedling pick-up device consisting of a path generator, pick-up pins, and a pin driver. This device could extract 30 seedlings per minute with a success ratio of 97%. A pincette-type end-effector designed by Han *et al*. (2015b) included two fingers and four pins. The seedling pick-up test was performed using the prototype, showing that the prototype satisfied the functional. Yu (2012) and Yu *et al*. (2019) developed a rotary seedling pick-up mechanism, which features a more fluctuation of the transmission ratio, allowing for a non-uniform continuous motion. An analysis and optimization software developed by their team was used to obtain a set of optimal parameters that meet the operation requirements. The test results of the prototype showed that the success ratio of seedling pick-up reached 93.8%. Nevertheless, it is difficult to process non-circular gear. Cui *et al*. (2013) designed a geared five-bar linkage seedling pick-up device to solve this problem, and its feasibility and rationality were experimentally verified. However, the gripper type requires precise control for speed and position.

In addition, the parameters of key components of the seedling pick-up mechanism significantly influence the mechanism's performance. Solving the optimization model for the seedling pick-up mechanism belongs to a nonlinear optimization problem with considerable constraints and decision variables. In recent years, with the development of evolutionary algorithms, it has been proved that they are suitable for solving complex engineering optimization problems (Liu *et al*., 2015). Among these methods, PSO (particle swarm optimization) and SA (simulated annealing) have received more and more scholars' attention for their simple principle, good speed, and ease of implementation.

Consequently, the existing seedling pick-up mechanisms are relatively complex in structure. Most seedling pick-up mechanisms are mechanical drive or cylinder drive, which is difficult to realize the precise control for speed and clamping force. Besides, the optimization problem of the seedling pick-up mechanism is also challenging. Therefore, we developed a novel four-claw seedling pick-up mechanism to integrate penetration and clamping into one process, picking up seedlings stably and effectively. A brushless DC (direct current) servo motor characterized by small size, large torque, and high controlling precision was adopted. This motor can realize precise control for speed and clamping force through a control algorithm. Moreover, the optimization of the seedling pick-up mechanism is a complex multi-parameter and nonlinear optimization problem. So, the hybrid PSO-SA algorithm was adopted to solve the optimization model of it.

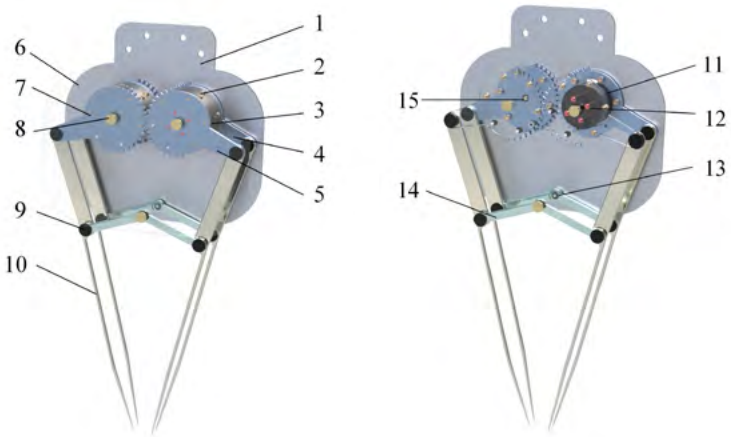
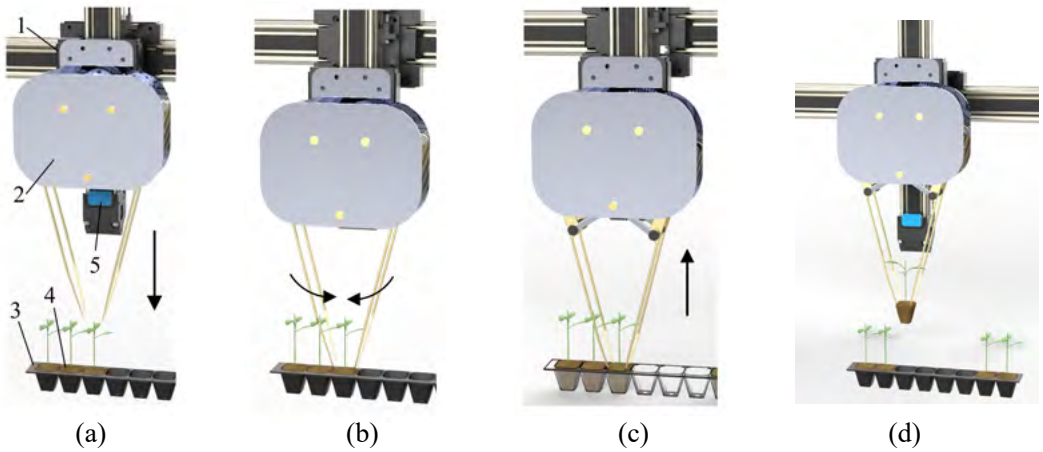


Figure 1. Structure of the seedling pick-up mechanism: exterior structure (a); interior structure (b). 1) mounting plate 1; 2) screw; 3) sleeve flange; 4) driving link 3; 5) driving link 2; 6) mounting plate 2; 7) driving link 1 8) small shaft; 9) interlocking screw; 10) pick-up pins; 11) servo motor; 12) connecting screw rod; 13) circlip; 14) connecting link; 15) bearing.



(a) (b) (c) (d)

Figure 2. Working process of the seedling pick-up device for picking up seedlings: descending (a), picking up seedlings (b), clamp seedlings (c), extract seedlings (d). 1) slider; 2) seedling pick-up mechanism; 3) plug tray; 4) seedling; 5) guide rail.

Material and methods

Design requirements of the seedling pick-up mechanism

The functions of the seedling pick-up device are to extract seedlings from the pot, transfer them, and feed them into the transplanting unit (Brewer, 1994). The seedling pick-up mechanism should steadily perform seedling pick-up without damaging the seedlings and the substrate (Han *et al*., 2015a). The lower part of the seedling substrate is usually more robust than the upper part, so clamping it from the lower part helps to reduce damage to it (Han *et al*., 2013a). Besides, the best opening of pick-up pins was 2-3 mm lower than the pot width (Choi *et al*., 2002b). With the increase in the number of pick-up pins, the stability of picking up seedlings also increases (Li *et al*., 2017).

In conclusion, the optimal trajectory of pick-up pins should meet the following requirements: (i) inserting into the lower part of the substrate; (ii) keeping a safe distance from the inner wall and bottom of the cell; (iii) clamping the substrate with more pick-up pins.

Development of seedling pick-up mechanism

Structure of seedling pick-up mechanism

The seedling pick-up mechanism consists of the mounting plate, a servo motor, driving and connecting links, and pick-up pins. As shown in Fig. 1, the Servo motor is connected to Driving link 2 through a connecting screw rod. Driving link 2 meshes with Driving link 1, with Driving link 2 is also connected to Driving link 3 with a sleeve flange. The servo motor rotates clockwise at a constant speed, and Driving link 2 is steered by the Connecting screw rod. The meshing of Driving link 2 and 1 achieves the clockwise rotation of Driving link 2 and 3 and the counterclockwise rotation of Driving link 1. As the Driving link moves inward, the pick-up pins approach the substrate in the cell and insert it. After the Pick-up pins clamp the seedling, the pick-up mechanism is lifted by lifting devices, and the seedling is extracted from the cell. Then the horizontal slider transfers the seedling pick-up mechanism to a specific position for releasing the seedling.

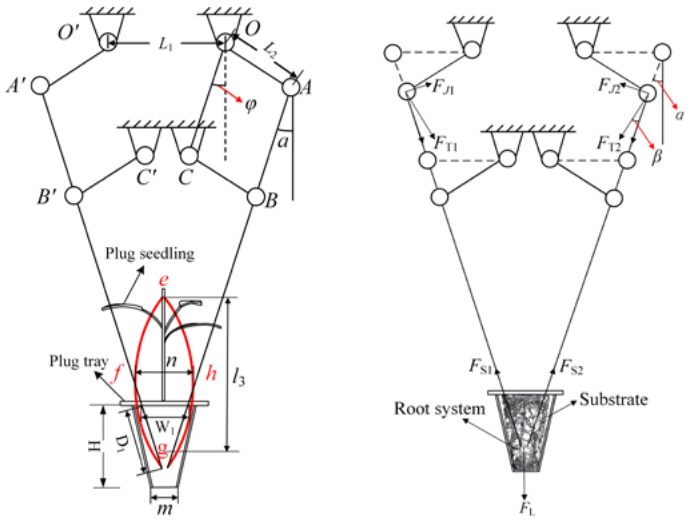
Working principle of seedling pick-up mechanism

Initially, the pick-up pins open and the pick-up mechanism move down with the slider. Then, the pick-up pins gradually approach the surface of the substrate (Fig. 2b). As the driving link rotates inward, the pins insert into the substrate. Until the substrate is clamped completely (Fig. 2c). As shown in Fig. 2d, the seedling is extracted with the upward movement of the slider. The pick-up pins are opened at the discharge point, then the driving link rotates outward, and the seedling is released.

Determination of structural parameters

Fig. 3 shows that O and O' are the rotation center of the driving link OA and $O'A'$, respectively. C and C' is the rotation center of the connecting link BC and $B'C'$ individually. L_1 is the distance between point O and O', L_2 is the length of the driving link OA, and φ is the angle of the y axis intersected with the line OC.

The curve *e-f-g-h* is the planned trajectory for picking up seedlings. The pick-up pins should insert into the substrate along the curve *f-g-h* for seedling extraction. Point *g* is the completion position of picking up seedlings, and points *f* and *h* are the releasing positions. When picking up seedlings, the seedling pick-up mechanism should meet the conditions in Eq. (1).



(a) (b)

Figure 3. Motion diagram of the seedling pick-up mechanism.

$$\begin{cases} W_1 < n \\ D_1 \cos\varphi < H \end{cases} \tag{1}$$

When the seedling pick-up mechanism is ready to move upward, the force analysis is shown in Fig. 2b. F_L is the resistant force for extracting plug seedlings, which is determined by the mass of the plug seedlings, the adhesion between the substrate and the pot (Miao *et al*., 2013). F_{J1} and F_{J2} are the clamping forces of the seedling pick-up mechanism on the seedling, which is determined by the substrate's deformation and compressive properties (Han *et al*., 2013b). F_{S1} and F_{S2} are the frictions between the pick-up pins and the substrate, which are mainly composed of the slip friction force F_f and the sliding resistance F_{fa}. Considering the homogeneity of the substrate, $F_{S1} = F_{S2} = F_f + F_{fa} = \mu (F_{J1}+ps)$, where μ is the friction factor between the substrate and the pick-up pins, and s is the contact area. Given the small contact area between the substrate and the pick-up pins, F_{fa} can be ignored, so $F_{S1} = F_{S2} = \mu F_{J1}$ (Hu, 2011). The mechanical balance equation is shown in Eq. (2).

$$\begin{cases} F_{S2}\sin\alpha + F_{J1}\cos\alpha = F_{S1}\sin\alpha + F_{J2}\cos\alpha \\ (F_{J1}+F_{J2})\sin\alpha + (F_{S1}+F_{S2})\cos\alpha \geq F_L \end{cases} \tag{2}$$

Assuming that the substrate is a homogeneous material, then F_{J1} and F_{J2} have the same effect, Eq. (3) can be obtained:

$$F_{J1} = F_{J2} \geq \frac{F_L}{2(\sin\alpha + \mu\cos\alpha)} \tag{3}$$

Because the clamping force on the substrate is generated by the motor, the force of the motor on the pick-up pins is F_{T1} and F_{T2}. When the pick-up pins grasp the substrate and start to move upward, analyzing the force of pick-up pins, Eq. (4) can be obtained:

$$F_{T1} = \frac{F_{J1}}{\sin\beta} \tag{4}$$

Therefore, to extract the seedling successfully, the force generated by the motor must meet the constraint conditions in Eq. (5).

$$F_{T1} \geq \frac{F_L}{2\sin\beta(\sin\alpha + \mu\cos\alpha)} \tag{5}$$

where F_L is the resistant force determined by the agronomic conditions for seedling raising (Miao *et al*., 2013) and is the clamping angle of the seedling pick-up mechanism.

It can be found from Eq. (4) that the clamping force decreases with the increase of the clamping angle. However, if the clamping angle is too large, the insertion depth of the pick-up pins will be affected. Choi *et al*. (2002a) found that the pick-up pins were inserted into the substrate with a gap of 2-3 mm lower than the pot wall and that inserting the substrate as deep as possible contributed to the seedling extraction. In order to ensure the maximum clamping angle and meet the specifications of the plug tray at 128 holes and 72 holes in Table 1, the clamping angle was designed to be 18° theoretically. Consequently, the pick-up pins and the pot wall can maintain a 2-3 mm insertion gap to have an initial opening of 28-35 mm and a maximum insertion depth of 37 mm. The separation force of cucumber, tomato, and other plug seedlings from the pot has been measured as 0.97-2.93 N (Han, 2014). The static friction factor of the substrate and pick-up pins is 0.49-0.54 (Han *et al*., 2013b). Therefore, according to Eqs. (2) - (5), it was estimated that the motor torque needed to overcome the

Table 1. Specifications of plug tray.

Specification	Size (L*W), mm²	Central distance of hole (d), mm	Depth of hole (h), mm	Upper caliber (a*b), mm	Lower caliber (c*c), mm
12*6	280*540	45	45	40*40	20*20
16*8	280*540	32.5	42	32*32	14*14

maximum separation force of seedlings from its pot was 0.64 N·m.

In order to satisfy the requirements for picking up and releasing seedlings, avoiding mechanical interference, and not causing damage to the seedlings, the initial value of each parameter is (Eq. (6):

$$(L_1 \quad L_2 \quad L_3 \quad \varphi) = (84 \quad 60 \quad 265 \quad 16) \tag{6}$$

where L_3 is the length of pick-up pins, and φ is the angle of the y axis intersected with the line *OC*.

Design of control system

Hardware design of control system

The hardware of the control system includes three sections: the sensor used for signal obtaining, the controller used for processing the signal, and the driving unit to perform specific actions (Yang *et al*., 2020).

Selection of programmable controller

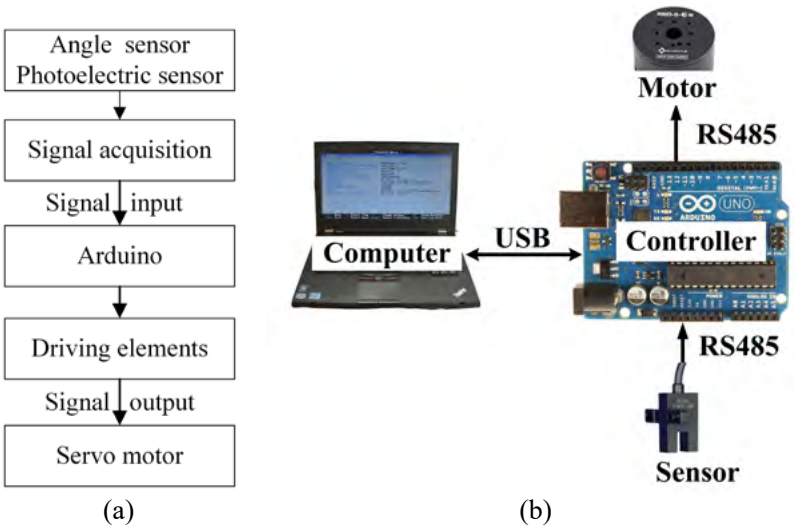
We adopted Arduino as the controller of the seedling pick-up mechanism and transferring device. The flow chart of the control system and the control system's communication are shown in Figs. 4a, and 4b, respectively. In this control system, Arduino was used for receiving the input signal from the sensor, processing the signal, and delivering the signal to the servo motor. Several key parameters must be considered in the controller selection, such as the processing speed and accuracy, the number of communication ports etc. Therefore, Arduino UNO was selected as the controller of our seedling pick-up mechanism.

Design of control system hardware circuit

The hardware circuit of the seedling pick-up mechanism and transplanting device is shown in Fig. 5: 1 is the angle sensor of the seedling pick-up mechanism; 2, 3 and 4 are the photoelectric sensors of transferring and the lifting devices, respectively; 5 and 6 are the servo motor of transferring devices; and 7 is the servo motor of the lifting device. A 24-V DC power supply powered the servo motor, and the angle sensor and photoelectric sensor were connected to the input pin of Arduino. The output pin of Arduino was connected to the A and B pins of the servo motor. The VCC (voltage-to-current converter) and GND (ground) pins of the servo motor were connected to the positive and negative terminals of the power supply, respectively. This control system is based on RS-485 communication.

Design of control system software

Arduino IDE 1.8.13 was used as the core programming software. The photoelectric sensor was used to detect the position of the slider retained on transferring and lifting



(a) (b)

Figure 4. Main control system: flow chart of control system (a) and communication of control system (b).

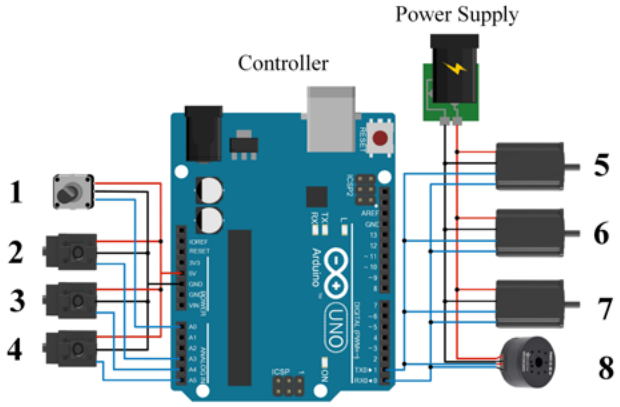


Figure 5. The hardware circuit of control system.

devices. The angle sensor measures the current angle of pick-up pins. When the seedling pick-up mechanism was transferred to the seedling picking position by the slider, the photoelectric sensor received and inputted the signal into the Arduino. Thus, the servo motors of transferring devices stop and then the seedling pick-up mechanism starts to pick up seedlings. When the current angle measured by the angle sensor reaches the predetermined value, the servo motor stops, and the seedling is clamped. Then the seedling is extracted from the pot by lifting devices and transferred to the releasing position.

Kinematic model of seedling pick-up mechanism

As shown in Fig. 6, the position of the driving link is AB when pick-up pins start to approach the cell. When the pick-up pins clamp the substrate completely, the position of the driving link is AB′, and the rotation angle of the driving link is δ during this process. Since the seedling pick-up mechanism is symmetrical structurally, half of it is analyzed.

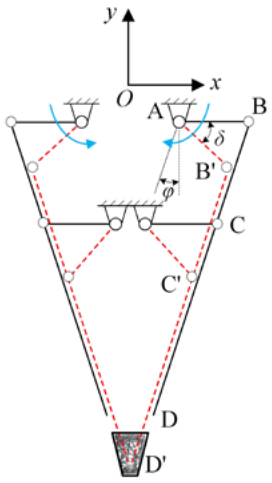


Figure 6. Kinematic model of the seedling pick-mechanism.

The coordinates of points A, B and D at initial position were as follows:

$$\begin{pmatrix} x_A & x_B & x_D \\ y_A & y_B & y_D \end{pmatrix} = \begin{pmatrix} \frac{L_1}{2} & \frac{L_1}{2}+L_2 & \frac{L_1}{2}+L_2-L_3\sin\varphi \\ 0 & 0 & -L_3\cos\varphi \end{pmatrix} \quad (7)$$

The coordinates of point D' can be expressed as Eq. (8):

$$\begin{cases} x_{D'} = \frac{L_1}{2} + L_2\cos\omega t - L_3\sin\varphi \\ y_{D'} = -L_2\sin\omega t - L_3\cos\varphi \end{cases} \quad (8)$$

Therefore, the trajectory equation of position D is shown in Eq. (9).

$$y = \sqrt{{L_2}^2 - \left(x - \frac{L_1}{2} + L_3\sin\varphi\right)^2} - L_3\cos\varphi \quad (9)$$

In this coordinate system, the position of the cell was assumed constant, so the equation of the inside wall of the pot is shown in Eq. (10):

$$y_1 = 3.98x - 338.5 \quad (10)$$

The velocity of point D is expressed in Eq. (11).

$$\boldsymbol{v} = v_x\boldsymbol{i} + v_y\boldsymbol{j} = \dot{x}\boldsymbol{i} + \dot{y}\boldsymbol{j} = (-\omega L_2\sin\omega t)\boldsymbol{i} + (-\omega L_2\cos\omega t)\boldsymbol{j} \quad (11)$$

The acceleration of point D is shown in Eq. (12).

$$\boldsymbol{a} = a_x\boldsymbol{i} + a_y\boldsymbol{j} = \ddot{x}\boldsymbol{i} + \ddot{y}\boldsymbol{j} = (-\omega^2 L_2\cos\omega t)\boldsymbol{i} + (\omega^2 L_2\sin\omega t)\boldsymbol{j} \quad (12)$$

Parameter optimization of seedling pick-up mechanism

Design variables

Considering that the trajectory of point D is related to L_1, L_3 and φ, the design variables were selected as follows:

$$\mathrm{X} = (L_1 \quad L_{BD} \quad \varphi) = (x_1 \quad x_2 \quad x_3) \quad (13)$$

Objective function

According to the requirements of the seedling picking trajectory, when pick-up pins approach the top of the cell, the deviation between the trajectory curve of point D and the predetermined trajectory curve should be minimized. So, the objective function is defined in Eq. (14).

$$f = \sqrt{3600 - \left(14 - \frac{x_1}{2} + x_2\sin x_3\right)^2} - x_2\cos x_3 + 274.8 \quad (14)$$

Constraint condition

Given design requirements, the assembly restrictions, and non-interference mechanically, the size of each part should meet constraints in Eq. (15):

$$\begin{cases} 3600 - \left(14 - \dfrac{x_1}{2} + x_2 \sin x_3\right)^2 \geqslant 0 \\ \dfrac{x_1}{2} - x_2 \sin x_3 + 60 > 16 \end{cases} \tag{15}$$

The upper and lower bounds of each decision variable are shown in Eq. (16):

$$\begin{pmatrix} lb \\ ub \end{pmatrix} = \begin{pmatrix} 75 & 255 & 14 \\ 90 & 300 & 20 \end{pmatrix} \tag{16}$$

Hybrid PSO-SA optimization

Principle of the PSO algorithm

Particle swarm optimization (PSO), as a kind of swarm intelligence, simulates the biological behavior of a bird flock seeking food and searching for the optimal value in the search space through individual cognitive and social cognitive (Eberhart & Kennedy, 1995; Kennedy & Eberhart, 1995; Shi & Eberhart, 1998). The PSO algorithm treats each individual in the population as a particle without volume or weight in the search space, representing a possible solution. The particle flies at a certain speed in the search space, and the best position experienced by the particle is the optimum solution found by the particle itself. The flight speed of the particle is dynamically adjusted by the flight experience of the particle and the group, and the optimal solution is obtained iteratively.

In the beginning, a group of particles are created in the search space $S \in \mathbb{R}^n$ and ${X_k}^i = \{{X_1}^i, {X_2}^i, \cdots, {X_n}^i\}^T$ is considered as the current position of particle k. Following this, the best value of the particle k ${P_k}^b = \{{P_1}^b, {P_2}^b, \cdots, {P_n}^b\}^T$ and the global optimal value $P^g = \{{P_1}^g, {P_2}^g, \cdots, {P_n}^g\}^T$ in iteration i are calculated. Then, the velocity and position of the particle are updated using Eqs. (17) and (18). The loop terminates until the convergence condition is satisfied.

$$v_k^{i+1} = \omega v_k^i + c_1 R_1 \cdot (P_k^b - X_k^i) + c_2 R_2 \cdot (P^g - X_k^i) \tag{17}$$

$$X_k^{i+1} = X_k^i + v_k^{i+1} \tag{18}$$

where v_k is the velocity of the particle k, R_1 and R_2 are random numbers which are generated between 0 and 1, c_1 and c_2 are learning rate.

The PSO algorithm has a faster convergence speed and better global search capability than the other optimization algorithm. However, it has the problem of premature convergence and poor local search ability (Angeline, 1998).

Principle of the SA algorithm

Simulated Annealing (SA), inspired by the physical annealing process of solids, is a popular intelligent optimization algorithm. According to Metropolis *et al.* (1953) and Genovese *et al.* (2005), the probability of the atom reaching equilibrium at temperature T is $e^{-\triangle E/(kT)}$, E is the energy at temperature T, $\triangle E$ is the E change, k is the Boltzmann constant. The optimization problem is simulated by solid annealing, and energy E is regarded as objective function f and temperature T as the control parameter. During the iteration of the algorithm, Eq. (19) was used to decide whether to accept the new solution.

$$p = \begin{cases} 1 & if \ \ f(X_{i+1}) \leqslant f(X_i) \\ e^{-\frac{\triangle f}{T}} & Otherwise \end{cases} \tag{19}$$

where f is the fitness function, $\triangle f = f(X_{i+1}) - f(X_i)$, and T is the controlling parameter. The acceptance probability decreases with decreasing temperature, and the Eq. (20) is usually used as a temperature decrement method.

$$T_{i+1} = R_T T_i \tag{20}$$

where T_0 is the initial temperature, and R_T is a positive constant between 0.8 and 0.999. SA algorithm has been successfully applied to many fields and achieve excellent effect (Di Sciuva *et al*., 2003; Liu *et al*., 2014).

The hybrid algorithm of PSO-SA

For the past few years, many hybrid PSO-SA algorithms have been proposed, which can be divided into three categories. Accelerating the convergence of SA by adopting a good start position generated by PSO (Xia & Wu, 2006), incorporating the Metropolis *et al.* (1953) acceptance principles into the PSO algorithm (Shieh *et al*., 2011), and combining PSO cycles with the SA iterations (Costa *et al*., 2011).

In this paper, a hybrid PSO and SA algorithm was adopted, aiming to improve the performance of the algorithm (Javidrad & Nazari, 2017). If there are no changes during a period of PSO, a new global optimal position is generated using SA to replace the old one. Equation was used to guide the movement of particles in the search space to seek the optimal solution of an objective function. Fig. 7 shows the flow chart of the hybrid PSO-SA algorithm.

Three parameters are involved in the hybrid PSO-SA algorithm: the population size of the particle (P_s), the original temperature (T_0), and the Markov chain length (L_M).

Table 2. Ratio of the main components of the matrix.

Saturaid	Chicken litter	Husk	Soybean meal	Nitrogen	Phosphates	Potash	Ferrous sulfate
0.6	0.1	0.1	0.08	0.005	0.003	0.003	0.007

In this paper, P_s=50, T_0=100, and L_M=100 were used. The algorithm was implemented using MATLAB (R2018a). The convergence curve for the objective function is shown in Fig. 8. It can be found that the proposed hybrid PSO-SA algorithm converges to the global optimum point much faster than either PSO or SA algorithm. Moreover, the hybrid PSO-SA algorithm has better stability compared to the SA algorithm. Finally, the value of the optimized decision variable is determined, which is L_1=87.5 mm, L_2=277 mm, φ=18°.

Kinematic simulation validation

A kinematic simulation analysis was conducted to validate the trajectory curve of the pick-up pins. We assumed that each part of the mechanism is made of duralumin and the weight of the seedling is negligible (Hu, 2011). A simulation cycle refers to pick-up pins moving from their initial position to clamping the seedling completely. In addition, Qi *et al*. (2011) found that the maximum acceleration the seedling can withstand is 45 m/s^2.

Firstly, the 3D model of the seedling pick-up mechanism was created using SolidWorks (3D solid modeling CAD software). Then, the 3D model was imported into the kinematic simulation software ADAMS (Automatic Dynamic Analysis of Mechanical System), the mass properties of each part were determined, and the required constraints were built. The corresponding motion was established, and then the simulation was performed. The driving function of the mechanism is shown in Eq. (21), with a simulation time of 0.03 s and a step number of 2000; the motion simulation was conducted.

$$step(time,0,0d,0.05,30d)+step(time,0.05,0d,0.08,0)+step(time,0.08,0d,0.1,-30d) \quad (21)$$

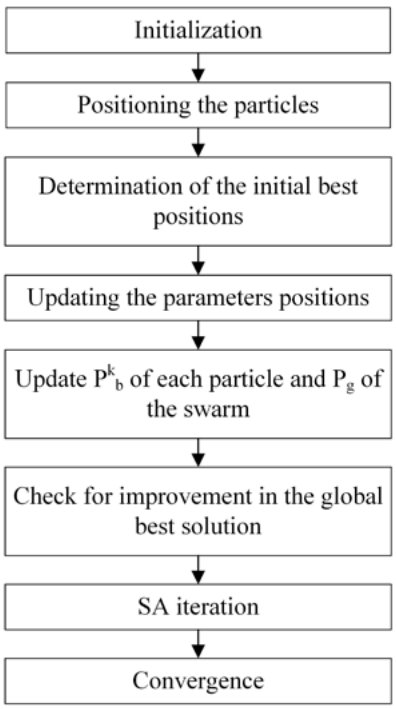


Figure 7. Flow chart of hybrid PSO-SA algorithm.

Fig. 9 shows the trajectory curve of the pick-up pins, where A is the completion point of the seedling picking, and B is the initial point, indicating that when the seedling pin reaches point B, the distance between the inside wall of the cell and the pick-up pins is 2 mm. When pick-up pins clamp the seedling, the end of the pick-up pins reaches point A, which is the lower part of the cell. Therefore, the trajectory curve of pick-up pins meets the design requirements.

Seedling pick-up tests of the mechanism

The prototype was constructed to verify the efficiency of the optimized seedling pick-up mechanism, and the performance tests were carried out in the laboratory, as shown in Fig. 10. The room temperature was 28℃, and the relative humidity 41%. A potted tray with 16×8 cells was used for the tests, with tomato seedlings 39 days old. The ratio of the main components of the matrix is shown in Table 2.

Some researchers have also found that the leave's damage caused by the pick-up pins does not significantly affect seedling growth after transplanting. Given these factors, the success ratio in picking up seedlings is defined in Eq. (22):

$$T_S = \frac{S}{N} \times 100\% \quad (22)$$

where S is the sum of seedlings successfully released, N is the total number of seedlings tested.

The seedling release rate and the damage rate are also important to evaluate the performance of the seedling pick-up mechanism, which can be expressed in Eqs. (23) and (24):

$$T_L = \frac{M}{N} \times 100\% \quad (23)$$

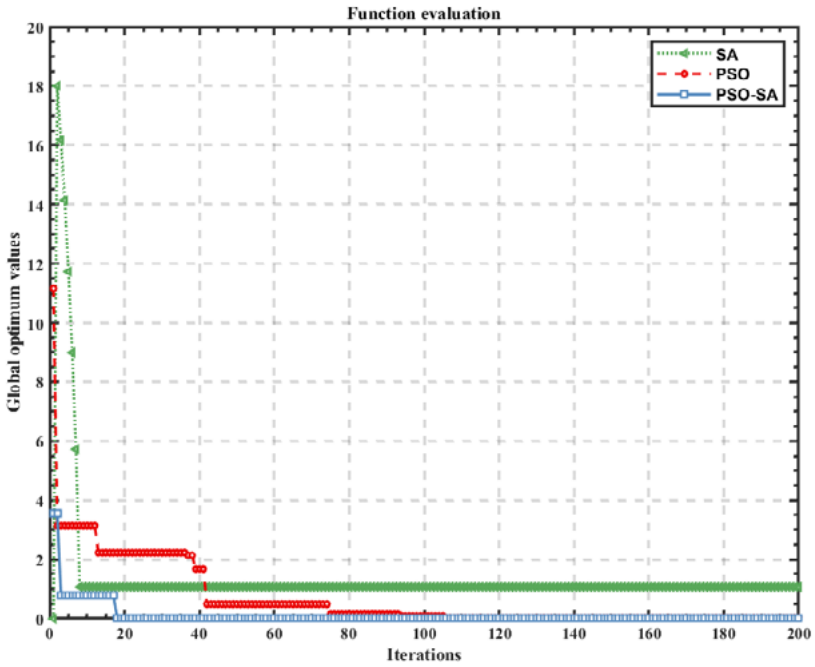


Figure 8. Convergence behavior of objective function by the proposed hybrid PSO-SA algorithm.

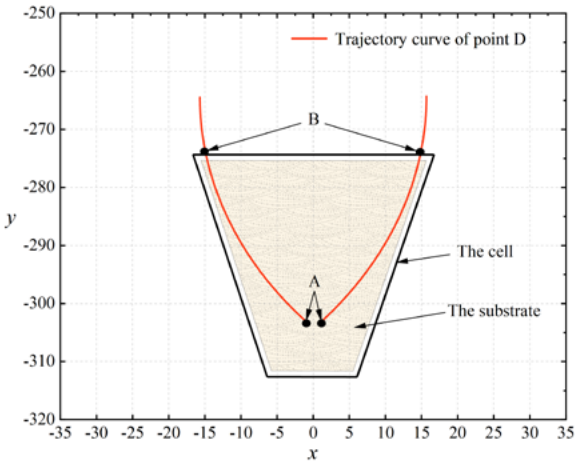


Figure 9. The trajectory curve of point D.

$$T_D = \frac{M_1 - M_2}{M_1} \times 100\% \quad (24)$$

where M is the number of seedlings successfully released, and N is the total number of seedlings tested; M_1 is the mean mass of seedlings before transplanting, and M_2 is the mean mass after transplanting.

The success rate and release rate showed how smoothly the mechanism picked, transferred, and released seedlings. The damage rate was used to evaluate the damage to seedlings caused by the seedling pick-up mechanism. The transplanting frequency was 50, 70, and 90 plants per minute, respectively, and Table 3 provides the statistical results of the test.

The Design-Expert was used to analyze the experimental results, and the regression equation between the three experimental indexes and various factors was obtained.

Results

Fig. 11 provides the simulation result of the seedling pick-up mechanism, indicating that the velocity and acceleration are smooth and there is no significant change. Therefore, the mechanism can ensure the seedling pick-up mechanism motion in continuity and smoothness with a small impact. From the time of t = 0 s, the pick-up pins were inserted into the substrate. During this process, the velocity of pick-up pins slowly increased, contributing to reducing the damage to the substrate. In addition, the maximum acceleration was 37.68 m/s^2, which was lower than the maximum acceleration the seedling could withstand. The maximum clamping force of pick-up pins was 5.096 N, meeting the requirements of extracting seedlings from the pot. In addition, the clamping force of pick-up pins slowly increased, preventing the seedlings from damaging. The simulation result show that our optimized mechanism meets the requirements for picking up seedlings and reduces the damage to the substrate.

The variance analysis of evaluation indexes is shown in Table 4, which indicates that the experimental model was significant (p<0.05) and the more significant among the three factors was the influence of seedling pick-up rate

Table 3. Test results of the prototype.

Seedling pick-up rate (plant/min) x_1	Moisture content (%) x_2	N (plant)	S (plant)	M (plant)	M_1 (plant)	M_2 (plant)	T_S (%)	T_L (%)	T_D (%)
50	50	128	112	108	9.86	9.33	87.50	84.38	5.38
	60	128	116	112	10.19	9.76	90.63	87.5	4.22
	70	128	109	109	9.63	9.22	85.16	85.16	4.26
70	50	128	108	101	9.37	8.86	84.38	78.91	5.44
	60	128	113	107	10.44	9.93	88.28	83.59	4.89
	70	128	103	97	9.56	9.04	80.47	75.78	5.44
90	50	128	106	102	10.71	10.14	82.81	79.69	5.32
	60	128	107	103	9.62	9.17	83.59	80.47	4.68
	70	128	99	95	9.76	9.12	77.34	74.22	6.56
Sum		1152	973	934	89.11	84.58	84.46	81.08	5.13

N, total number of seedlings tested. S, sum of seedlings successfully released. M, number of seedlings successfully released. M_1, mean mass of seedlings before transplanting. M_2, mean mass of seedlings after transplanting. T_S, success ratio in picking up seedling. T_L, release rate of seedling. T_D, damage rate of seedling.

on the evaluation index. The regression equation between the evaluation index and the three factors is as follows (x_1 is the seedling pick-up efficiency, and x_2 is the moisture content):

— Success ratio of seedling pick-up:

$$T_S = 87.41 - 3.26x_1 - 1.95x_2 - 0.78x_1x_2 + 0.13{x_1}^2 - 4.56{x_2}^2 \quad (25)$$

— Release rate of seedling pick-up:

$$T_L = -49.11 - 0.59x_1 + 5.41x_2 - 0.008x_1x_2 + 0.006{x_1}^2 - 0.042{x_2}^2 \quad (26)$$

— Damage rate of seedling pick-up:

$$T_D = 42.05 - 0.089x_1 - 1.169x_2 - 0.003x_1x_2 - 0.0005{x_1}^2 + 0.008{x_2}^2 \quad (27)$$

The test result showed that the mean success ratio of picking up seedlings reached 84.46%, the release rate of the seedlings was 81.08% and the percentage of damaged seedlings dropped to 5.13%.

Therefore, the performance of the seedling pick-up manipulator was excellent, allowing for application in the automatic transplanter. However, we can observe in Table 3 that the success ratio of picking up seedlings decreases with the seedling pick-up rate increase.

Comparing the three different moisture contents of the soil matrix, when the moisture content is about 60%, the success ratio of picking seedlings is highest. This phenomenon may be because the moderate moisture content leads to the consolidation of the roots of plug seedlings.

For a visual representation of the relationship between experimental factors and evaluation indexes, the response surface analysis was performed using Design Expert 12. Fig. 12 shows that the combination of the seedling pick-up rate and the moisture content had a significant influence on the success ratio of seedling pick-up, the release rate of seedling, and the damage rate of seedlings. Fig. 12 indicates that when the moisture content does not change, the success ratio of seedling pick-up and the release rate of seedling decrease with the increase of seedling extraction frequency. The success ratio of seedling pick-up and the release rate reached their maximum, while the damage rate reached its minimum when the moisture content was about 60%. Therefore, compared with the moisture content, the seedling pick-up rate was the main factor affecting the success ratio of seedling pick-up and release rate of the seedling.

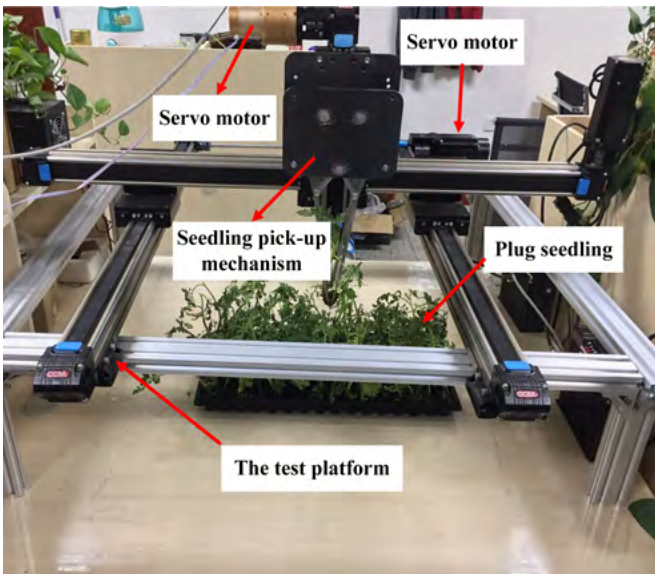


Figure 10. Performance test of the seedling pick-up mechanism.

Table 4. Variance analysis.

	Variance source	Model	x_1	x_2	x_1x_2	x_1^2	x_2^2	Residual	Cor total
Success ratio, %	Sum of squares	130.6	63.7	22.89	2.45	0.033	41.53	1.89	132.49
	Mean square	26.12	63.7	101.05	36.32	3.89	0.052	65.88	
	F value	41.44	101.05	36.32	3.89	0.052	65.88		
	p value	0.006	0.002	0.009	0.143	0.834	0.004		
Release rate, %	Sum of squares	152.49	85.58	10.19	9.77	12.23	34.72	4.77	157.27
	Mean square	30.50	85.58	10.19	9.77	12.23	34.72	1.59	
	F value	19.17	53.80	6.41	6.14	7.69	21.83		
	p value	0.018	0.005	0.085	0.089	0.069	0.019		
Damage rate, %	Sum of squares	3.97	1.21	0.002	1.39	0.070	1.29	0.211	4.18
	Mean square	0.794	1.21	0.002	1.39	0.070	1.29	0.070	
	F value	11.31	17.31	0.034	19.84	0.993	18.39		
	p value	0.037	0.025	0.865	0.021	0.393	0.023		

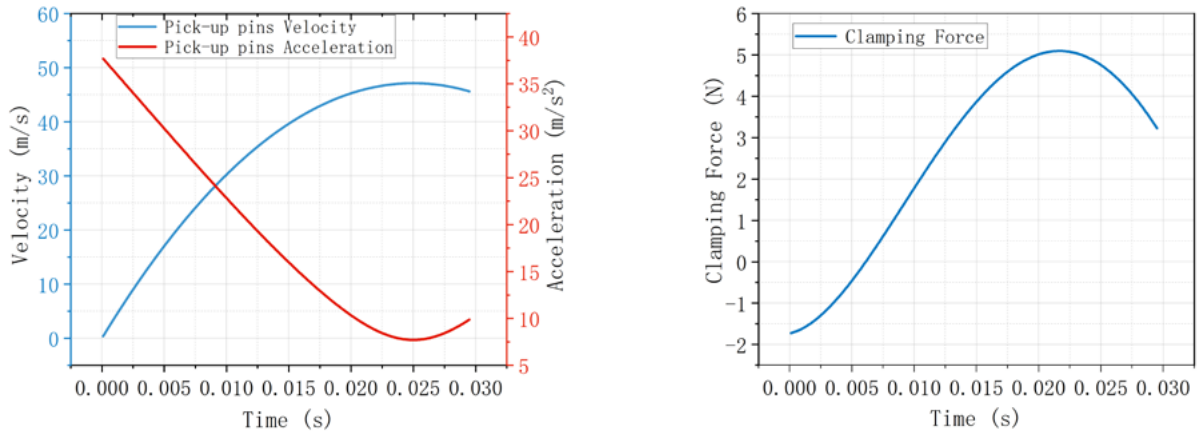
Cor total, sum of x_1, x_2, x_1x_2, x_1^2, x_2^2 and Residual.

Discussion

As a critical component of automatic transplanters, the structure and parameters of the seedling pick-up mechanism have a significant influence on the realization of efficient and low-damage seedling picking. In this paper, we developed a novel four-claw seedling pick-up mechanism. Compared with the majority of existing two-claw mechanisms, our seedling picking mechanism improves the success ratio of seedling pick-up by increasing the number of claws. Moreover, we adopted a motor instead of the currently widely used pneumatic actuator as the driven device. The clamping force can be precisely controlled by the motor, thus reducing the damage rate of the seedling.

Secondly, we used the hybrid PSO-SA algorithm to obtain the optimal parameter of the seedling pick-up mechanism for the first time. This optimization method has two advantages compared with the current optimization method: (i) the hybrid PSO-SA algorithm was more efficient and had higher accuracy than the trial-and-error method; (ii) compared with the single PSO or SA algorithm we used before, the convergence speed and accuracy of hybrid PSO-SA has improved greatly.

However, we also found that the success rate of seedling pick-up decreased with the increase of seedling pick-



(a) (b)

Figure 11. Simulation result of the seedling pick-up mechanism: velocity and acceleration curve (a) and clamping force curve (b).

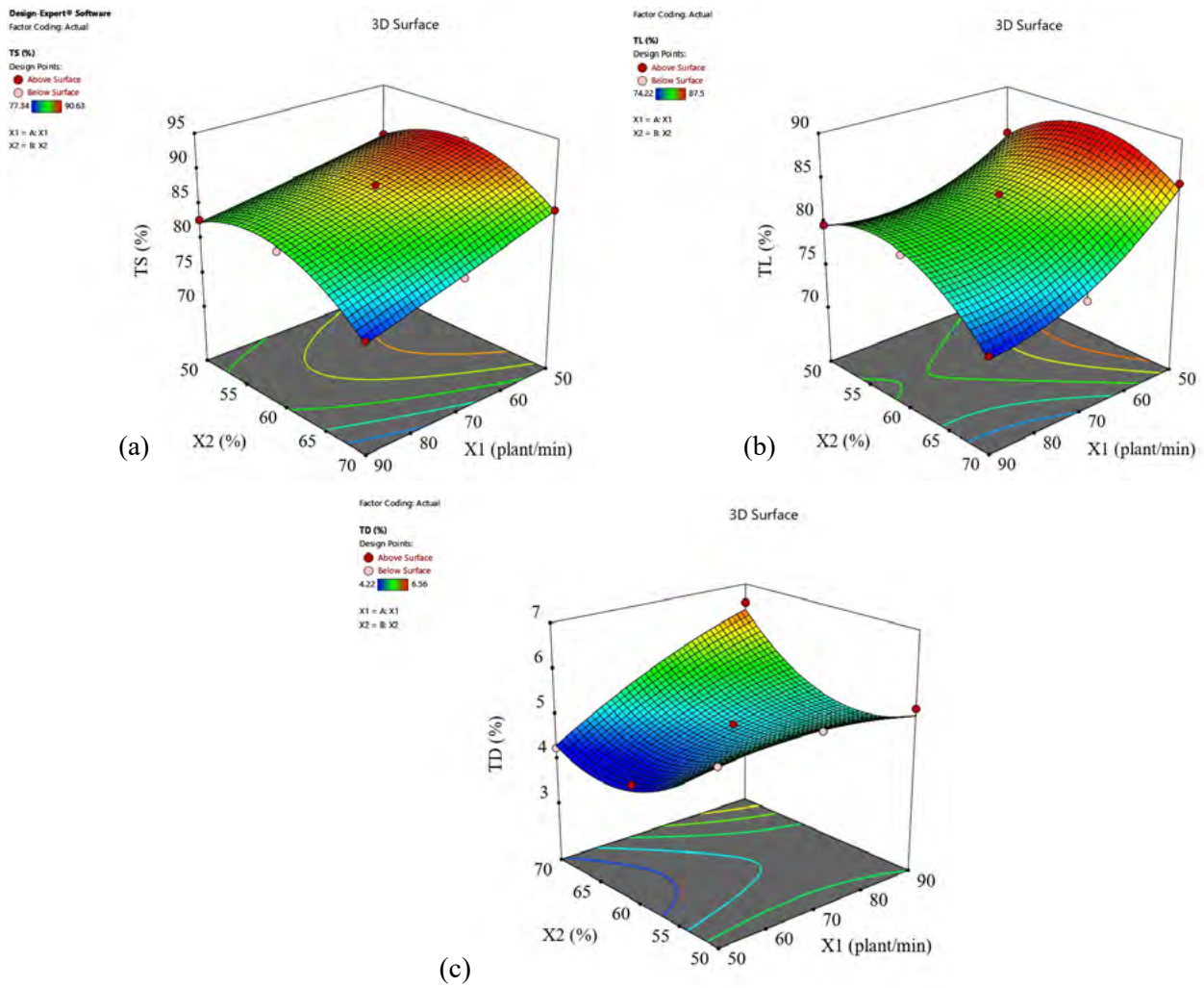


Figure 12. Response surface of each factor to qualified index: success ratio (a), release rate (b), and damage rate (c).

up rate by analyzing the test results. This phenomenon may be caused by the linear acceleration and deceleration of lifting and transferring devices. We can conclude that in addition to the mechanism itself, the control algorithms of the control system also significantly influence the success rate of seedling pick-up. In this case, improving the control algorithm may help to solve this problem.

Authors' contributions

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Formal analysis: Fei Li, Weibing Wang.
Funding acquisition: Weibing Wang, Jin Lei.
Investigation: Fei Li, Bao Song.
Methodology: Fei Li, Weibing Wang.
Project administration: Weibing Wang.
Resources: Weibing Wang, Jin Lei.
Software: Fei Li.
Supervision: Jin Lei, Weibing Wang.
Validation: Fei Li, Weibing Wang.
Visualization: Fei Li.
Writing – original draft: Fei Li.
Writing – review & editing: Jin Lei, Bao Song.

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