horticulturae

Article

Design and Experimental Study of a Traction Double-Row Automatic Transplanter for Solanum Lycopersicum Seedlings

Dong Ji [1,2,†], Limin Liu [1,†], Fandi Zeng [1], Guangteng Zhang [1], Yinzeng Liu [1], Hongwei Diao [1], Subo Tian [2] and Zhihuan Zhao [1,*]

1 College of Mechanical and Electronic Engineering, Shandong Agriculture and Engineering University, Jinan 250100, China; dongjisdaeu@163.com (D.J.); liulimsy2882@163.com (L.L.); zfd19508@163.com (F.Z.); gt13323894566@163.com (G.Z.); lyz19971024@163.com (Y.L.); dhw_0823@163.com (H.D.)
2 College of Engineering, Shenyang Agricultural University, Shenyang 110866, China; j18341895506@126.com
* Correspondence: zhaozhihuan@sdaeu.edu.cn
† These authors contributed equally to this work.

Abstract: The most important part of fruit cultivation is transplanting, which can be completed efficiently by an automatic transplanter. In this study, an automatic solanum lycopersicum transplanter was developed. It is primarily composed of the following devices: a seedling tray fixator, a mechanical transplanting arm, double horizontal driving modules, double vertical driving cylinders, a seedling separation device, double-crank five-bar planting devices, a power distribution system, and a PLC control system. An experimental test on an automatic transplanter was carried out on dry land. The experimental results showed that when the planting frequency was 80 plants/(min·row), the transplanting success rate was 93.89%, the missed planting rate was 1.58%, the replanting rate was 0.65%, the lodging rate was 1.94%, and the exposed seedling rate was 1.94%. Each device of the automatic transplanter was coordinated to complete the transplanting process. The automatic transplanter met the operation requirements, and it not only transplanted in dry land but also provided a theoretical basis for fruit cultivation in solar greenhouses in the future.

Keywords: agricultural machinery; fruit transplanting; PLC control

Citation: Ji, D.; Liu, L.; Zeng, F.; Zhang, G.; Liu, Y.; Diao, H.; Tian, S.; Zhao, Z. Design and Experimental Study of a Traction Double-Row Automatic Transplanter for Solanum Lycopersicum Seedlings. *Horticulturae* **2024**, *10*, 692. https://doi.org/10.3390/horticulturae10070692

Academic Editor: Qiaomei Wang

Received: 27 May 2024
Revised: 23 June 2024
Accepted: 27 June 2024
Published: 29 June 2024

1. Introduction

The technique of seedling transplant has been widely promoted due to its advantages, such as avoiding natural disasters and improving the survival rate of seedlings. Seedling transplant has become a crucial aspect of greenhouse agricultural production due to the widespread adoption of seedling nurseries. However, in China, the predominant method of transplanting seedlings is through the use of semi-automatic transplanters [1–3]. Picking and throwing seedlings must be performed manually, which not only has high costs regarding labor but also has the drawbacks of limited speed and easily fatigued manual labor, which limit the improvement of transplanting efficiency. As a result, it is crucial to develop an automatic transplanter that can increase transplanting efficiency, decrease labor requirements, and promote the growth of the vegetable industry [4,5].

Research and development of transplanters in agriculture began in the 1980s. During this period, researchers developed some transplanters to transfer seedlings from high-concentration to low-concentration trays in greenhouses to grow plants [6,7]. After that, many other transplanters were designed, and they mainly focused on several aspects, especially mechanical engineering, control engineering, and machine vision [8–10]. Some developed countries, such as Japan, the United States and Italy, have begun to study dryland transplanting technology and developed an automatic transplanter suitable for the field. Europe and the United States had the large multi-row automatic transplanter. Japan developed the small transplanter [11–13]. Some transplanter achievements have been reported. Tong et al. [14] applied RTK GPS and machine vision to an automatic transplanter, which improved the intelligence of the automatic transplanter and saved labor. Liu et al. [15] developed an automatic transplanter that comprises a seedling storage device, seedling-taking device, seedling-ejecting device, pinch device, transplanting device, and monitor system. The experiment was carried out, and the broccoli seedlings were the experimental object. The success rate was 75% when the transplanting frequency was 95 plants/min, and the seedling leakage rate was 5%. Li et al. [16] developed and optimized a seedling-taking device, which used cylinders as the driving mode. The standard 72-hole seedling tray of cucumber seedlings was the test object. The experimental result showed that the damage rate of seedlings was 1.6% and the success rate was 95.3%. Various commercial automatic transplanters with distinct structures have been developed and widely adopted. The Visser Horti Systems Company has been dedicated to conducting research on horticulture machinery since 1967. The Pic-O-Mat Vision transplant machine has the ability to remove inadequate seedlings using a vision system [17]. Most transplanters developed in Europe and the United States tend to be large. To improve the efficiency of potted seedling transplanting, mechatronics technology and a special seedling tray have been applied. It is costly and not suitable for the current situation of tray seedling in China [18,19]. The majority of transplanters developed in Japan and Korea are mechanical constructions, using a combination of different structures for automatic transplanting. A more complex mechanical structure causes machine maintenance difficulties, restricting its development in China [20,21].

In this study, an automatic transplanter was designed that used PLC control technology, sensor technology, mechanical transmission, pneumatic technology, and stepper motor drive technology according to China's agronomic practices. A traction-type, double-row high-speed automatic transplanter was developed, and a field transplanting experiment was conducted to assess the overall performance. It not only transplanted in dry land but also provided a theoretical basis for fruit cultivation in solar greenhouses in the future.

2. Materials and Methods

The automatic transplanter is composed of a mechanical transplanting arm (1), double vertical driving cylinders (2), double horizontal driving modules (3), twelve transplanting manipulators (4), a double seedling separation device (5), a seedling tray fixator (6), and double-row planting devices (7). The overall structure is shown in Figure 1. The model of the seedling tray for the automatic transplanter is shown in Figure 2. The tractor pulls the automatic transplanter to move forward and drives the seedling separation device, planting device, and air compressor. Other electric components are powered by a battery. The size and working parameters of the automatic transplanter are shown in Table 1.

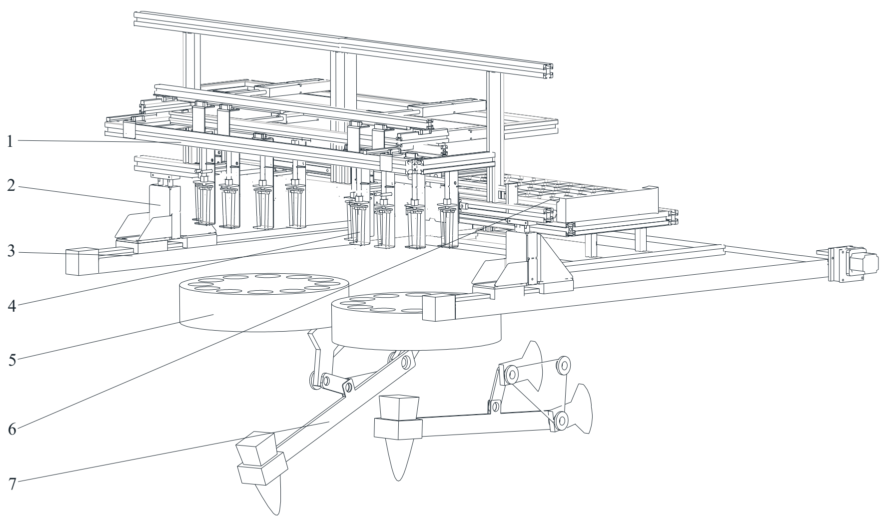

Figure 1. Overall structure schematic diagram of the automatic transplanter. 1. Mechanical transplanting arm; 2. vertical driving cylinder; 3. horizontal driving module; 4. transplanting manipulator; 5. seedling separation device; 6. seedling tray fixator; 7. double-row planting devices.

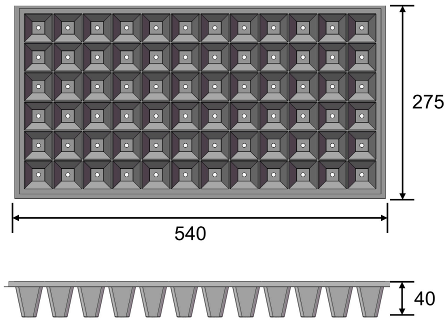

Figure 2. Seedling tray (mm).

Table 1. The size and working parameters of the automatic transplanter.

Item	Parameter	Unit	Item	Parameter	Unit
Boundary dimension (length × width × height)	1250 × 1100 × 1550	mm	Matching tractor model	304	
Number of operators	2		Row spacing	300–500	mm
Driving pressure	0.5	MPa	Total weight	423	Kg
Frequency	80	plants/min·row	Battery voltage	24	V

2.1. Working Principle of Automatic Transplanter

The mechanical transplanting arm drives the movement of the transplanting manipulators to pick up and transport the seedlings to the seedling separation device, which is mainly composed of double first-stage propulsion cylinders (1), a transplanting manipulators guide rod (2), a frame (3), a guide rail (4), double lateral propulsion cylinders (5), and double second-stage propulsion cylinders (6). When the automatic transplanter takes seedlings, the mechanical transplanting arm is lifted by the vertical driving cylinder and, at the same time, transported to the seedling tray placement frame by the horizontal driving module. The transplanting manipulators are installed on the transplant arm. The lateral propulsion cylinder resets and drives the transplanting manipulator to merge, which is above the first row of the seedling tray. The cylinders of the transplanting manipulators drive the needles, taking out the seedlings in the tray. The structure and seedling picking process of the mechanical transplanting arm are shown in Figure 3.

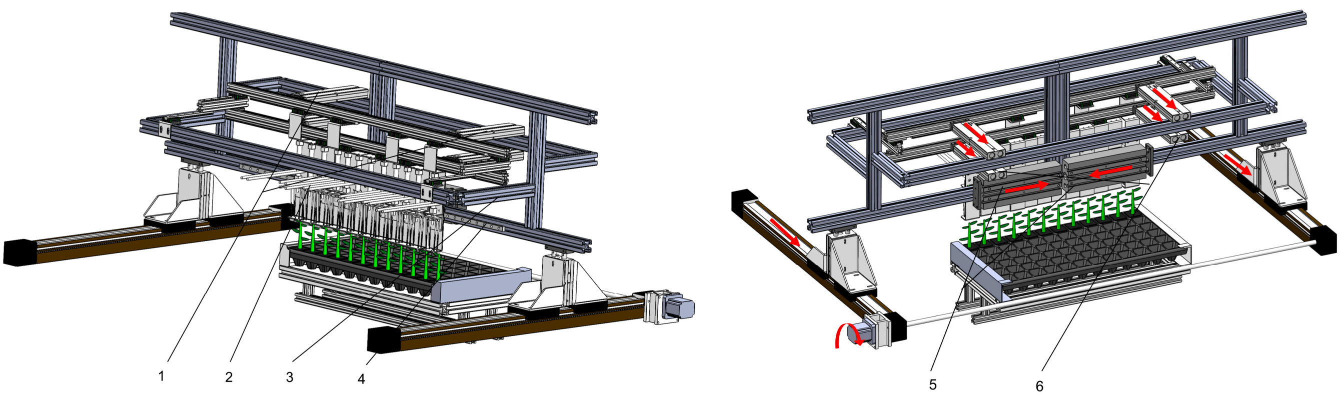

Figure 3. Structure and seedling picking process of mechanical transplanting arm. 1. First-stage propulsion cylinder; 2. Transplanting manipulators guide rod; 3. Frame; 4. Guide rail; 5. Lateral propulsion cylinder; 6. Second-stage propulsion cylinder. The mechanical transplanting arm is equipped with twelve transplanting manipulators, corresponding to the whole row of the seedling tray. The stepper motor and all cylinders move in the direction indicated by the arrow to complete the seedling picking process.

In the process of seedling feeding, the horizontal driving module drives the mechanical transplanting arm to transport the seedlings to the top of the seedling separation device. Under the action of the first-stage propulsion cylinder and the second-stage propulsion cylinder, the seedling claw is directly above the seedling separating device. The vertical driving cylinders and the seedling manipulator cylinders are retracted, and the seedlings are placed in the seedling separation device. The seedling feeding process of the mechanical transplanting arm is shown in Figure 4. The seedling separation device rotates to take the seedlings into the planting device. Finally, the seedlings are transplanted in the field by the planting device.

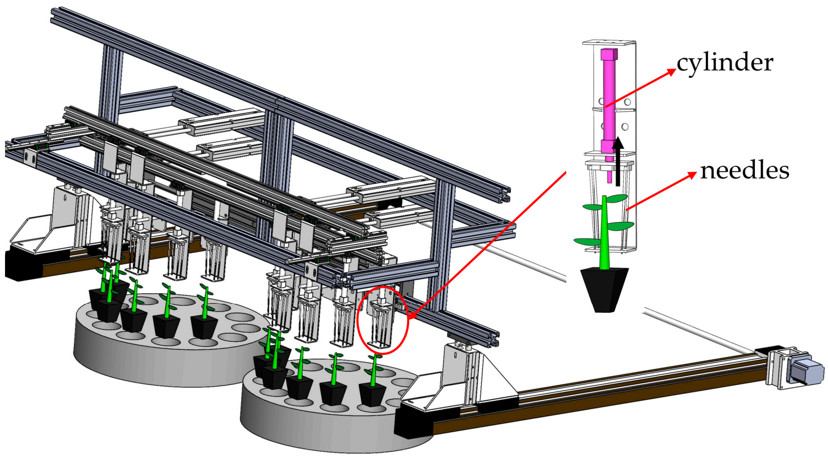

Figure 4. Seedling feeding process of mechanical transplanting arm. The cylinder retracts, and drives the needle to retract. The seedling falls into the cavity plate seedling separation device.

2.2. Transplanting Manipulator

When seedlings are transferred by the transplanting manipulator, the needles interact with the soil substrate of the seedling. A mechanical model was built to represent the interaction between the "seedling substrate-manipulator needle" during seedling taking. The model is illustrated in Figure 5. In this context, d represents the distance between the insertion point of the manipulator needle and the centerline of the seedling pipeline. h represents the depth to which the transplanting manipulator needle is inserted into the soil. G represents the weight of the seedling. K represents the adhesion force between the inner wall of the tray and the substrate soil. F_{N1} represents the normal force exerted by the manipulator needle. α represents the angle at which the needle of the transplanting manipulator is inserted into the seedling substrate. F_{f1} represents the frictional force between the seedling and the transplanting manipulator. F_T represents the total longitudinal lifting force.

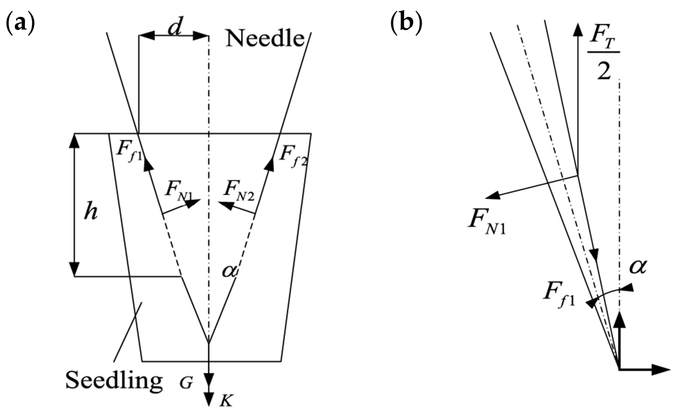

Figure 5. Force analysis of the seedling-taking process. (**a**) Force analysis on the seedling; (**b**) force analysis of one needle.

The adhesion force (K) is influenced by several parameters, including the moisture level of the seedling, the composition of the tray material, and the dimensions of the tray's inner wall. The experimental subject of this study were solanum lycopersicum seedlings. A method of experimentation was employed to assess the seedlings with water content ranging from 25% to 40%. The adhesion force was tested by a tensile pressure tester. (HP-50; Bino Instrument Company Ltd., Wenzhou, China), and water content was tested by a moisture content (DHG-9013; Yiheng Instrument Company Ltd., Shanghai, China). The value was shown in Table 2. The maximum value was 6.26 N. The maximum value was 6.26 N, chosen to ensure the seedling taking.

Table 2. Adhesion force experimental result.

Group One			Group Two		
Order	**Adhesion Force/N**	**Water Content/%**	**Order**	**Adhesion Force/N**	**Water Content/%**
1	5.86	33.2	6	5.02	26.9
2	5.63	31.5	7	5.68	33.1
3	5.72	33.1	8	5.07	27.6
4	5.15	28.2	9	6.17	37.5
5	6.26	37.4	10	5.42	31.2

The parameters were calculated as follows:

$$F_f = \mu F_{N1} \tag{1}$$

$$F_f \cos\alpha + F_{N1} \sin\alpha = (K+G)/2 \tag{2}$$

$$F_{N1} = (K+G)/2(\mu cos\alpha + sin\alpha) \tag{3}$$

As a seedling is successfully selected, the output clamping force is balanced with the adhesion force (K). Therefore, the seedling-taking process can be modelled as follows:

$$F_J/cos\alpha = (K+G)/2(\mu cos\alpha + sin\alpha) \tag{4}$$

$$F_T = 2\left[sin\alpha(F_{N1} + F_{N2}) + cos\alpha\left(F_{f1} + F_{f2}\right)\right] \tag{5}$$

$$F_{f1} = \mu F_{N1} \tag{6}$$

$$F_{f2} = \mu F_{N2} \tag{7}$$

$$Z \le F_T \tag{8}$$

The static friction coefficient (μ) is equal to 0.7. The shear force (F_J) and the longitudinal lifting force (Z) are related by the equation $Z = K + G$.

The formula above demonstrates that the seedling selection process must be counteracted by both the weight of the seedlings (G) and the frictional force (K) between the tray inner wall and the seedling substrate. Nevertheless, an extremely substantial lifting effort would result in shear damage to the horizontal orientation of the seedling. The force of the seedling needles depends on the horizontal shear force (F_J) that the seedling can withstand. Therefore, the total longitudinal lifting force (F_T) is calculated as follows:

$$F_T = 4F_{N1}(sin\alpha + \mu cos\alpha) \tag{9}$$

$$F_T = 4F_J(\mu cos\alpha + sin\alpha)/cos\alpha = 4F_J(\mu + tan\alpha) \tag{10}$$

An INSTRON 5944 testing machine was used to measure the seedling horizontal shear force (F_J), as shown in Figure 6a. A deformation of 5 mm was chosen as the maximum seedling shear force. Ten seedlings with water content ranging from 25% to 40% were chosen in the experiment, as shown in Figure 6b. The average shear force (F_J) measured was 5.8 N.

(a) (b)

Figure 6. Shear force experiment. (**a**) Shear force test platform; (**b**) experimental seedlings.

An experiment was conducted to determine the average gravity range of seedlings and the penetration angle (α). The results indicated that the average weight of the seedlings was 0.23 N, and the optimal range for the penetration angle (α) was between 4° and 12°. The adhesion force (K) was 6.26 N, and the shear force (F_J) was 5.8 N. The value of the penetration angle (α) was 8°. The drive force (F_J) and the cylinder internal diameter (D) can be determined using the following formulas:

$$Z = K + G = 0.23 + 6.26 = 6.49 \text{ N} \tag{11}$$

$$F_T = 4F_J(\mu + tan\alpha) = 19.5 \text{ N} \tag{12}$$

$$F_1 \geq F_T \cdot K_1 \cdot K_2/\eta \tag{13}$$

$$K_2 = 1 + a/g = 2 \tag{14}$$

$$F_1 \geq 19.5 \times 1.1 \times 2/0.9 \approx 47.7 \text{ N} \tag{15}$$

$$D = \sqrt{F_{pu}/0.65 \cdot p} = \sqrt{47.7/0.65 \cdot 5 \cdot 10^5} \approx 12.1 \text{ mm} \tag{16}$$

where η is the mechanical efficiency (0.90), K_1 is the safety factor (1.1), and K_2 is the operating condition coefficient. In the usual working state, the acceleration of the grasped seedling (a) was that of gravity (g).

The CDJ2B10-35 cylinder was chosen based on its design specifications of a working pressure (0.5 MPa) and output force (42.8 N). The cylinder had an internal diameter (15 mm) and a stroke (35 mm), which were smaller than the height of the tray (40 mm). The seedlings could be collected, and the tray could be preserved intact.

The transplanting manipulator includes a mounting rack (1), three cylinder mounting plates (2), a cylinder (3), a needle guide block (4), and two manipulator needles (5), as shown in Figure 7a. When the transplanting manipulator removes the seedlings from the tray, its four needles are propelled by the cylinder, penetrating the soil substrate and then closing. The seedlings are collected by the needles. When the seedlings are released by the transplanting manipulator at the discharge point, the four needles open and retract through the cylinder drive, completing the seedling-dropping process, as shown in Figure 7b,c.

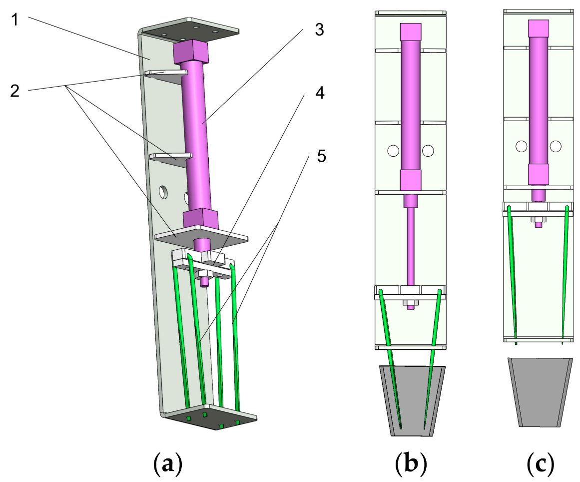

Figure 7. Transplanting manipulator and its working process. (**a**) Transplanting manipulator structure; (**b**) seedling-taking process; (**c**) seedling-dropping process. 1. mounting rack; 2. cylinder mounting plate; 3. cylinder; 4. needle guide block; 5. manipulator needle.

2.3. Seedling Tray Fixator

A seedling tray fixator was designed to fix the tray. The seedling tray fixator mainly consists of a bottom support frame (1), a baseboard (2), two guide bars (3), and two side plates (4), as shown in Figure 8. The two guide bars can fix the y-direction. The baseboard and side plates can fix the x- and y-directions. The tray can be fixed tightly in the seedling tray fixator.

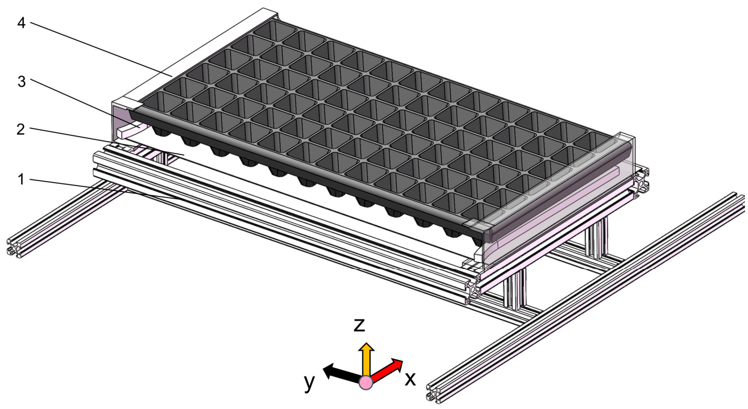

Figure 8. Seedling tray fixator. 1. Bottom support frame; 2. Baseboard; 3. Guide bar; 4. Side plate.

2.4. Planting Device

The speed and trajectory of the planting device affect the planting quality. In the planting process, the zero-speed planting method can improve the success rate of planting because seedlings are stationary relative to the ground. In the paper, the optimized structural parameters can be found by analyzing the motion of the double-crank five-bar mechanism, and the equations of each point are expressed using the rectangular coordinates method, as shown in Figure 9.

$$\begin{cases} x_Q = l_0 cos\beta_1 + l_2 cos\beta_4 \\ y_Q = l_0 sin\beta_1 + l_2 sin\beta_4 \end{cases} \tag{17}$$

$$\begin{cases} x_R = l_1 cos\beta_2 \\ y_R = l_1 sin\beta_2 \end{cases} \tag{18}$$

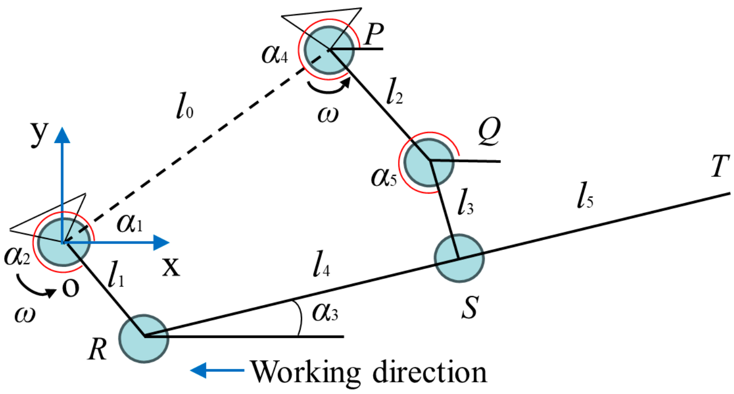

Figure 9. Kinematics operation model of five-bar planting mechanism.

According to the following vector Equation:

$$L_{oP} + L_{PQ} + L_{QS} = L_{oD} + L_{DC} \tag{19}$$

The following Equation can be obtained:

$$\begin{cases} l_o cos\beta_1 + l_2 cos\beta_4 + l_3 cos\beta_5 = l_1 cos\beta_2 + l_4 cos\beta_3 \\ l_o sin\beta_1 + l_2 sin\beta_4 + l_3 sin\beta_5 = l_1 sin\beta_2 + l_4 sin\beta_3 \end{cases} \tag{20}$$

Let $a = l_1 cos\beta_2 - l_o cos\beta_1 - l_2 cos\beta_4$, $b = l_1 sin\beta_2 - l_o sin\beta_1 - l_2 sin\beta_4$. The above equation can be expressed as follows:

$$l_3 cos\beta_5 = a + l_4 cos\beta_3 \tag{21}$$

$$l_3 sin\beta_5 = b + l_4 sin\beta_3 \tag{22}$$

Squaring the two sides of Equations (21) and (22), β_5 can be eliminated. The equation can be expressed as follows:

$$\left({l_3}^2 - a^2 - {l_4}^2 - b^2\right)/2l_4 = acos\beta_3 + bsin\beta_3 \tag{23}$$

Let, $cos\gamma = a/\sqrt{a^2+b^2}, sin\gamma = b/\sqrt{a^2+b^2}$, get β_3:

$$\beta_3 = arccos\frac{{l_3}^2 - a^2 - {l_4}^2 - b^2}{2l_4\sqrt{a^2+b^2}} + \beta \tag{24}$$

Substituting β_3 into Equations (4) and (5) yields β_5:

$$\beta_5 = arccos\left[l_1 cos\beta_2 - l_0 cos\beta_1 - l_2 cos\beta_4 + l_4 \cos(arccos\frac{{l_3}^2 - a^2 - {l_4}^2 - b^2}{2l_4\sqrt{a^2+b^2}} + \gamma)\right]/l_3 \tag{25}$$

The calculation of the displacement Equation for point S is as follows:

$$\begin{cases} x_S = l_1 cos\beta_2 + l_4 cos\beta_3 \\ y_S = l_1 sin\beta_2 + l_4 sin\beta_3 \end{cases} \tag{26}$$

The calculation of the displacement Equation for point T is as follows:

$$\begin{cases} x_E = l_1 cos\beta_2 + (l_4 + l_5) cos\beta_3 \\ y_E = l_1 sin\beta_2 + (l_4 + l_5) sin\beta_3 \end{cases} \tag{27}$$

where the structural parameters l_0 and β_1 are constants. The derivative of Equation (20) obtains the subsequent Equation:

$$\begin{cases} l_2\dot{\beta}_4 sin\beta_4 + l_3\dot{\beta}_5 sin\beta_5 = l_1\dot{\beta}_2 sin\beta_2 + l_4\dot{\beta}_3 sin\beta_3 \\ l_2\dot{\beta}_4 cos\beta_4 + l_3\dot{\beta}_5 cos\beta_5 = l_1\dot{\beta}_2 cos\beta_2 + l_4\dot{\beta}_3 cos\beta_3 \end{cases} \quad (28)$$

where $\dot{\beta}_2$, $\dot{\beta}_3$, $\dot{\beta}_4$ and $\dot{\beta}_5$ are the derivatives of β_2, β_3, β_4 and β_5 with respect to time (t), respectively. The input angular velocities of points o and P are denoted as ($\dot{\beta}_2$) and ($\dot{\beta}_4$), respectively.

The calculation of the angular velocity of QS rod according to Equation (28) is as follows:

$$\dot{\beta}_3 = \left[l_1\dot{\beta}_2 sin\beta_2 - l_2\dot{\beta}_4 sin\beta_4 + \left(l_2\dot{\beta}_4 cos\beta_4 - l_1\dot{\beta}_2 cos\beta_2\right) tan\beta_3\right] / (l_3 sin\beta_5 - l_3 cos\beta_5 tan\beta_3) \quad (29)$$

The velocity equation for point T is derived from the displacement equation:

$$\begin{cases} \dot{x}_E = -l_1\dot{\beta}_2 sin\beta_2 - (l_4 + l_5)\dot{\beta}_3 sin\beta_3 \\ \dot{y}_E = l_1\dot{\beta}_2 cos\beta_2 + (l_4 + l_5)\dot{\beta}_3 cos\beta_3 \end{cases} \quad (30)$$

Modify the transmission ratio of the chain drive mechanism to ensure that the duckbill's tangential velocity at the lowest point matches the rate of motion of the transplanter. In the opposite direction, this will cause zero-speed planting, which can improve the success rate of the planting process. The planting device is shown in Figure 10.

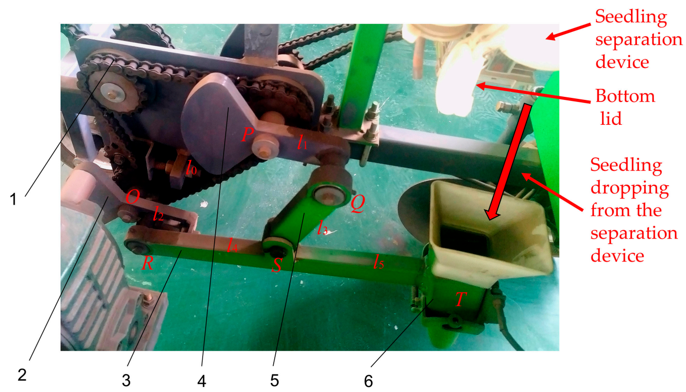

Figure 10. Planting device. 1. Chain drive device; 2. Crank III; 3. Long connecting bar; 4. Crank I; 5. Short connecting bar; 6. Duckbilled planter. The seedling separation device rotates, and when it moves to the top of the duckbill planting device, the bottom lid is opened. The seedlings drop from the separation device and fall into the duckbill.

The planting device is a double-crank five-bar mechanism. The chain drive device (1) drives crank II (2) and crank I (4) to move, and the two cranks rotate in the same direction at the same speed, driving the long connecting bar (3) and short connecting bar (5) to swing. The long connecting bar (3) is connected to the duckbill planter, and the duckbilled device moves in the established trajectory. When the duckbill planter reaches the top, the bottom lid of the separation device is opened, and the seedlings fall into the duckbill. When the duckbill planter reaches the lowest point, it is inserted into the soil, and the seedlings are planted into the soil.

2.5. Power Distribution and PLC Control System

(1) Power distribution

The power distribution system mainly consists of a lithium battery, a start/stop button, an emergency stop button, a contactor, circuit breakers, fuses, a voltage regulator, and a voltage boost module, as shown in Figure 11. The power distribution system provides electricity to the control systems and electrical components. The PLC, air pressure sensor, power shaft detection sensor, proximity switches and solenoid valves are powered by 24 VDC power supply. The horizontal drive module is driven by 48 V stepper motor, and other components are driven by the tractor power shaft and cylinder. The voltage boost module (Pin Shen, model: PDG300-24S48) is used to convert 24 VDC to 48 VDC to provide power for the stepper motor. According to the total power of the power consumption components and the working frequence, in order to ensure the safety of manual operators and power requirements, a 24 VDC, 40 AH lithium battery is selected as the power supply for the system.

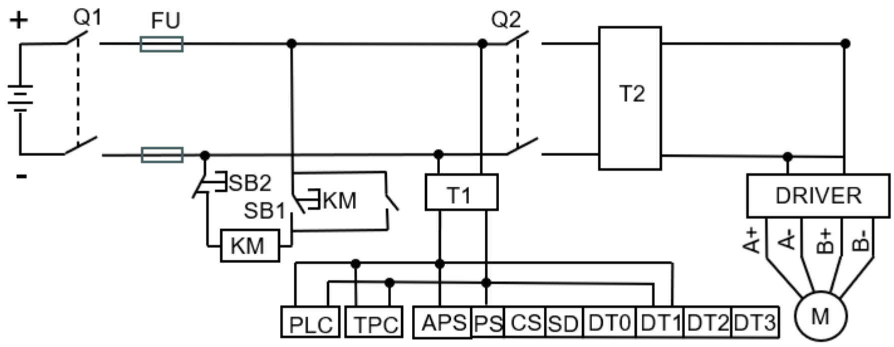

Figure 11. Schematic diagram of the power distribution system. Note: KM is the contactor; Q1 and Q2 are the breakers; FU are the fuses; T1 is the regulated switching power supply; T2 is the DC boost module; M is the stepper−motor−driving horizontal−driving module; APS is an air pressure sensor; PS are the proximity switches; CS is the counting sensor; and SD is a power shaft detection sensor.

(2) PLC control system

The PLC control system includes PLC, a stepper motor, cylinder solenoid valves, relays, an air pressure sensor, a counting sensor, and proximity switches. The PLC control system is shown in Figure 12. The main controller adopts Siemens S7-200 series 224xp PLC [22]. PLC receives the analog signals of the air pressure sensor and power shaft detection sensor and outputs the high-speed pulse signal to drive the stepper motor of the horizontal transmission module. PLC controls the opening and closing of the solenoid valve through digital signals. All actuators are controlled by the PLC control system, and each device coordinates and cooperates to complete the automatic transplanting operation.

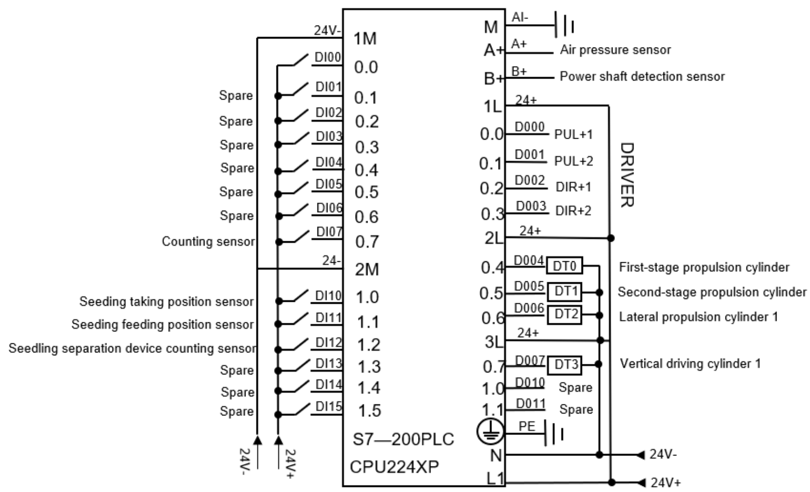

Figure 12. Schematic diagram of the PLC control system. Note: DT0 is the solenoid valve controlling the first−stage cylinder; DT1 is the solenoid valve controlling the second−stage cylinder; DT2 is the solenoid valve controlling the lateral propulsion cylinder; and DT3 is the solenoid valve controlling the vertical driving cylinder.

3. Experiment and Analysis

3.1. Experimental Condition

The transplanting experiment was carried out (Shuanglin Agricultural Machinery Co., Ltd., Sujiatun, China). The experimental environment was soft soil, without grass, gravel, etc. The experimental object were 72 holes solanum lycopersicum seedlings, the age of which was 30 days and the moisture content was 35%, as shown in Figure 13. Three plates of seedlings were transplanted into each group and five groups of experiments were carried out. The experimental pictures are shown in Figure 14.

Figure 13. Solanum lycopersicum seedlings.

Figure 14. Transplanting experiment. 1. Transplanting arm; 2. Transplanting manipulator; 3. Air compressor; 4. Planting device; 5. Seedling separation device; 6. Power distribution and PLC control system; 7. Battery. Traction double-row automatic transplanter needs two operators. One person needs to drive the tractor, and the other needs to alter the seedling tray.

3.2. Experimental Indexes

In the continuous operation of transplanting, the transplanting success rate is generally used as an evaluation index according to the mechanical industry standard experimental method in the People's Republic of China Transplanter of dry land plant (JB/T 10291–2013). During the experiment, the success rate of transplanting was mainly affected by four aspects, namely, the exposed seedling rate, the lodging seedling rate, the leakage seedling rate and the replanting seedling rate.

(1) Exposed seedling rate

Seedling exposure refers to the failure of seedlings to be fully planted in the soil when the seedling substrate is exposed outside the pit, affecting normal growth. The formula for calculating the exposed seedling rate is as follows:

$$n_1 = U_1/U \times 100\% \tag{31}$$

where U_1 is the number of exposed seedlings and U is the total number of seedlings.

(2) Lodging seedling rate

Lodging refers to the angle between the mid-vertical line and the ground after the seedling is transplanted into the soil, which is bigger than 60°. The formula for calculating the lodging seedling rate is as follows:

$$n_2 = U_2/U \times 100\% \tag{32}$$

where U_2 is number of lodging seedlings and U is the total number of seedlings.

(3) Leakage seedling rate

Leakage seedling refers to the location where the seedlings should be planted but there are no seedlings. The formula for calculating the leakage seedling rate is as follows:

$$n_3 = U_3/U \times 100\% \tag{33}$$

where U_3 is number of leakage seedlings and U is the total number of seedlings.

(4) Replanting seedling rate

Replanting refers to the planting of at least two seedlings in the same location. The formula for calculating the replanting seedling rate is as follows:

$$n_4 = U_4/U \times 100\% \tag{34}$$

where U_4 is number of replanting seedlings and U is the total number of seedlings.

(5) Success rate

The success rate is the ratio of the number of successful plants to the total number of plants. The formula for calculating the success rate is as follows:

$$L = (1 - n_1 - n_2 - n_3 - n_4) \times 100\% \tag{35}$$

where L is the success rate.

3.3. Results and Discussion

The experimental results and the rate of each index are shown in Tables 3 and 4. When the transplanting frequency was 80 plants/(min·row), the average transplanting success rate was 93.89%, the average seedling rate was 1.94%, the average lodging rate was 1.94%, the average seedling leakage rate was 1.58%, and the average replanting rate was 0.65%. The experiment shows that the main defects of automatic transplanter are an exposed seedling, lodging seedling and leakage seedling. These defects are mainly caused by the following factors:

(1) The planting device is affected by the vibration of the machine during the movement, which causes the seedling to collide with the planting device during the process of falling into the soil; in the process of collision, zero-speed planting was affected, resulting in an increase in the exposed seedling rate;
(2) When the transplanting frequency is too fast (greater than 80 plant/(min·row)), more precise cooperation between the devices is required; the planting device completes transplanting; at the moment, the planting device is unearthed and contacts the seedling substrate, stem or leaf, resulting in an increase in the lodging rate;

(3) There are a few seedlings with weak roots, so the shear resistance is poor; in the process of seedling taking, the transplanting manipulator destroys the seedlings, resulting in no seedlings in the planting device and an increase in the leakage seedling rate.

Table 3. Experimental results.

Group Number	Number of Successful Transplanting	Number of Exposed Seedlings	Number of Lodging Seedlings	Number of Leakage Seedlings	Number of Replanting Seedlings
1	201	4	6	3	2
2	202	5	4	4	1
3	204	4	3	3	2
4	202	5	4	3	2
5	205	3	4	4	0

Table 4. The rate of each index.

Group Number	Success Rate/%	Exposed Seedling Rate/%	Lodging Seedling Rate/%	Leakage Seedling Rate/%	Replanting Seedling Rate/%
1	93.05	1.85	2.78	1.39	0.93
2	93.52	2.31	1.85	1.85	0.46
3	94.44	1.85	1.39	1.39	0.93
4	93.52	2.31	1.85	1.39	0.93
5	94.91	1.39	1.85	1.85	0

In order to ensure the success rate, the appropriate transplanting frequency of the automatic transplanter is no more than 80 plants/(min·row). The seedling age and water content are suitable. In the future, reducing the size of the automatic transplanter from the double row to the single row to adapt to the limited space of the solar greenhouse should be considered. This study also provides a theoretical basis for fruit cultivation in solar greenhouses.

Next, we will also improve the intelligence of the transplanter and increase the monitoring system with multi-sensor fusion to further improve the success rate of the seedling-taking process and increase the applicability of the transplanter in different working scenarios. In terms of seedling taking, the matrix loss rate is further reduced, and it is used as an experimental index to measure the transplanting effect.

4. Conclusions

(1) When the extraction force of the transplanting manipulator is too large, it will cause shear damage to the seedlings.

(2) The experimental results showed that when the planting frequency was 80 plants/(min·row), the transplanting success rate was 93.89%, the missed planting rate was 1.58%, the replanting rate was 0.65%, the lodging rate was 1.94%, and the exposed seedling rate was 1.94%. The machine met the operation requirements.

Author Contributions: Conception D.J., L.L. and Z.Z.; methodology F.Z., S.T. and D.J.; formal analysis, G.Z., Y.L. and L.L.; resources, S.T.; date curation, D.J., H.D. and G.Z.; investigation, D.J., Y.L. and L.L., experiment S.T., H.D. and D.J. funding acquisition, Z.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by Program for Innovative Research Team in SDAEU (sgykycxtd2020-03).

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The authors would like to give special thanks to Sujiatun Shuanglin Agricultural Machinery Co., Ltd. for providing the experimental field.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Ankit, S.; Sanjay, K. Design and development of a vegetable plug seedling transplanting mechanism for a semi-automatic transplanter. *Sci. Hortic.* **2024**, *326*, 112773.
2. Vlahidis, V.; Roșca, R.; Cârlescu, P.M. Evaluation of the Functional Parameters for a Single-Row Seedling Transplanter Prototype. *Agriculture* **2024**, *14*, 388. [CrossRef]
3. Wu, W.; Zhang, Z.; Zhang, X.; He, Y.; Fang, H. Application of visual inertia fusion technology in rice transplanter operation. *Comput. Electron. Agric.* **2024**, *221*, 108990. [CrossRef]
4. Ji, D.; Tian, S.; Wu, H.; Zhao, B.; Gong, Y.; Ma, J.; Zhou, M.; Liu, W. Design and experimental verification of an automatic transplant device for a self-propelled flower transplanter. *J. Braz. Soc. Mech. Sci. Eng.* **2023**, *45*, 420. [CrossRef]
5. Syed, T.N.; Jizhan, L.; Xin, Z.; Shengyi, Z.; Yan, Y.; Mohamed, S.H.A.; Lakhiar, I.A. Seedling-lump integrated non-destructive monitoring for automatic transplanting with Intel RealSense depth camera. *Artif. Intell. Agric.* **2019**, *3*, 18–32. [CrossRef]
6. Hwang, H.; Sistler, F.E. A robotic pepper transplanter. *Appl. Eng. Agric.* **1986**, *2*, 2–5. [CrossRef]
7. Tmg, K.; Giacomelli, G.; Shen, S. Robot workcell for transplanting of seedlings part I-layout and materials flow. *Trans. ASAE* **1990**, *33*, 1005–1010. [CrossRef]
8. Jin, X.; Tang, L.; Li, R.; Zhao, B.; Ji, J.; Ma, Y. Edge recognition and reduced transplantation loss of leafy vegetable seedlings with Intel RealsSense D415 depth camera. *Comput. Electron. Agric.* **2022**, *198*, 107030. [CrossRef]
9. Li, M.; Xiao, L.; Ma, X.; Yang, F.; Jin, X.; Ji, J. Vision-based a seedling selective planting control system for vegetable transplanter. *Agriculture* **2022**, *12*, 2064. [CrossRef]
10. Ye, B.; Zeng, G.; Deng, B.; Yang, C.; Liu, J.; Yu, G. Design and tests of a rotary plug seedling pick-up mechanism for vegetable automatic transplanter. *Int. J. Agric. Biol. Eng.* **2020**, *13*, 70–78. [CrossRef]
11. Tsuga, K. Development of fully automatic vegetable transplanter. *Jpn. Agric. Res. Q.* **2000**, *34*, 21–28.
12. Mazzetto, F.; Calcante, A. Highly automated vine cutting transplanter based on DGNSS-RTK technology integrated with hydraulic devices. *Comput. Electron. Agric.* **2011**, *79*, 20–29. [CrossRef]
13. Kumar, P.; Raheman, H. Automatic feeding mechanism of a vegetable transplanter. *Int. J. Agric. Biol. Eng.* **2012**, *5*, 20–27.
14. Tong, J.; Shi, H.; Wu, C.; Jiang, H.; Yang, T. Skewness correction and quality evaluation of plug seedling images based on Canny operator and Hough transform. *Comput. Electron. Agric.* **2018**, *155*, 461–472. [CrossRef]
15. Liu, D.; Gong, Y.; Zhang, X.; Chen, X.; Wang, G.; Zhang, X. Design and experiment of dry-farming cantaloupe transplanter under water. *Agriculture* **2022**, *12*, 796. [CrossRef]
16. Li, B.; Gu, S.; Chu, Q.; Yang, Y.; Xie, Z.; Fan, K.; Liu, X. Development of transplanting manipulator for hydroponic leafy vegetables. *Int. J. Agric. Biol. Eng.* **2019**, *12*, 38–44. [CrossRef]
17. Jin, X.; Li, M.; Li, D.; Ji, J.; Pang, J.; Wang, J.; Peng, L. Development of automatic conveying system for vegetable seedlings. *EURASIP J. Wirel. Commun. Netw.* **2018**, *2018*, 1–9. [CrossRef]
18. Ji, J.; Cheng, Q.; Jin, X.; Zhang, Z.; Xie, X.; Li, M. Design and test of 2ZLX-2 transplanting machine for oil peony. *Int. J. Agric. Biol. Eng.* **2020**, *13*, 61–69. [CrossRef]
19. Paradkar, V.; Raheman, H.; Rahul, K. Development of a metering mechanism with serial robotic arm for handling paper pot seedlings in a vegetable transplanter. *Artif. Intell. Agric.* **2021**, *5*, 52–63. [CrossRef]
20. Jiang, Z.; Hu, Y.; Jiang, H.; Tong, J. Design and force analysis of end-effector for plug seedling transplanter. *PLoS ONE* **2017**, *12*, e0180229. [CrossRef]
21. Xie, S.; Yang, S.; Liu, J. Development of the seedling taking and throwing device with oblique insertion and plug clipping for vegetable transplanters. *Trans. CSAE* **2020**, *36*, 1–10.
22. Cheng, C.; Lin, J.; Zhang, H.; Wang, Q.; Xi, L.; Wang, L.; Luo, C. Design and Research of Power Battery Temperature Control by PLC. *Front. Comput. Intell. Syst.* **2023**, *4*, 63–66. [CrossRef]