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RESEARCH ARTICLE

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Development of a riding-type fully automatic transplanter for vegetable plug seedlings

Luhua Han (Han, LH)[1], Hanping Mao (Mao, HP)[1], Jianping Hu (Hu, JP)[2] and Francis Kumi (Kumi, F)[3]

[1]*Key Laboratory of Modern Agriculture Equipment and Technology, Ministry of Education, Jiangsu University, Zhenjiang 212013, China.* [2]*High-tech Key Laboratory of Agricultural Equipment and Intelligence of Jiangsu Province, Zhenjiang 212013, China.* [3]*University of Cape Coast, School of Agriculture, Dept. Agricultural Engineering, Cape Coast 999064, Ghana.*

Abstract

Aim of study: The aim of this study was to develop a riding-type fully automatic vegetable seedling transplanter enabling continuous transplanting work on 2 rows simultaneously with plug seedlings fed automatically.

Material and methods: In design, the transplanter consists of a 4-wheel drive system, a seedling pick-up mechanism, a seedling feeding mechanism, a rotation discharging mechanism, a 2-row planting mechanisms, and a multi-source control unit. The 4-wheel drive system is a riding type well adapting to slops. The seedling pick-up mechanism could extract several seedlings at a time from the tray cells conveyed by the feeding mechanism, and then transfer them to the rotation discharging mechanism where they would be released into the 2-row planting mechanisms. The multi-source control unit was constructed to carry out the flexible automation of seedling transplanting. Being the first prototype, the performance tests under actual production conditions were conducted on a vegetable base.

Main results: The testing results showed that the developed fully automatic transplanter could well grasp seedlings from the trays, transfer them, discharge them, and plant them into the ground. The success ratio in picking up seedlings and the qualified percent in planting seedlings were all up to 90%, and the coefficient of variation of plant spacing was less than 5% at the working speed of 60 plants row^{-1} min^{-1}.

Research highlights: The overall planting effects could well meet the requirements of agronomy cultivation, and the quality of automatic transplanting was satisfactory.

Additional keywords: seedling transplanting; pick-up mechanism; flexible automation; PLC.

Abbreviations used: CV (coefficient of variation of plant spacing); Q (qualified percent of success in planting seedlings); Q_{PD} (qualified percent of planting depth); SR (success ratio in picking up seedlings).

Authors' contributions: LHH: main design of the prototype and its testing and analysis; HPM and JPH: overall conception of the prototype; FK: partial design of the prototype and the paper writing. All authors read and approved the final manuscript.

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Correspondence should be addressed to Hanping Mao: maohp@ujs.edu.cn

Introduction

Vegetable is a kind of vital and necessary agricultural product in urban and rural residents' life, and it is a considerable livelihood issue to ensure the vegetable supply (https://wenku.baidu.com/view/5138888d6529647d2728523f.html). China is the largest producer and consumer of vegetables in the world, with a production of 22 million hectares and a yield of 800 million metric tons in 2018. However, vegetable cultivation in China lags behind in terms of mechanization of transplanting and harvesting operations. With the development of plug seedlings in an orderly array, the mechanization of soil filling, seeding, germination, and the raising of seedlings has advanced and been widely practiced in production areas (Mao *et al.*, 2014). To speed up the seedling transplanting mechanization can be the priority for mechanization of vegetable production (Zhang *et al.*, 2013). Besides, the shortage of skilled labors and the increase of labor cost have strongly demanded China and other countries to develop vegetable transplanters that allow for high-speed operation and labor saving (Prasanna & Raheman, 2008; Zhang *et al.*, 2013; Mao *et al.*, 2014).

Various semi-automatic transplanters have been in marketing promotion, which can plant seedlings into the ground (Zhang *et al.*, 2013). However, these transplanters have a limited operating speed due to the need for manual feeding of one seedling cell after another. Long-term continuous operation is also unfeasible because of operators' work fatigue. Overall, seedling transplantation is still labor-intensive, inefficient, and not implemented in time. It often leads to non-uniform plant distribution (Prasanna & Raheman, 2011). Thereby, it is difficult to obtain comprehensive benefits from transplant production. More interests have been stirred up in fully automatic transplanting since the seedlings are in an orderly array that might be handled mechanically. Tsuga (2000) reported that three models of fully automatic vegetable transplanters were jointly developed by a research institution and some agricultural equipment companies. These prototypes are suitable for cell mold seedlings and pulp mold cell pot seedlings, mainly of leaf vegetables such as cabbage (*Brassica oleracea* L. var. *capitata* L.), Chinese cabbage (*Brassica pekinensis (Lour.)* Rupr.), and lettuce (*Lactuca sativa* L. var. *ramosa* Hort). Although these transplanters perform well, they are not widely practiced except for product exhibition in China. The reasons are that these transplanters require higher levels of site preparation, and in particular, the flexible standard trays. In addition, these transplanters are also economically unfeasible for local production of vegetable seedlings because of their high manufacturing costs.

Recently, many attempts have been made to develop an automatic transplanter on the basis of cultural practice for vegetable production in China. The relevant researches focus on the design of key mechanisms and their structure parameter optimization (Cui *et al.*, 2013; Hu *et al.*, 2013; Ni *et al.*, 2015; Wang *et al.*, 2015; He *et al.*, 2016). These researches have made a significant contribution to mechanized transplanting of vegetable seedlings in China. However, most of the done works only aim at some critical components, which is lacking in the integral systematicness for seedling transplanting. Considering seedlings to be living and flexible, transplanting operation is one of the important biosystems engineering in agricultural production (Mao *et al.*, 2014). Therefore, synergistic innovation, both from horticultural and engineering perspectives, must be further strengthened in terms of transplanting efficacy, success in extracting seedlings, and much adaptability to different tray sizes and configurations (Parish, 2005).

The goal of this work was to develop a riding-type fully automatic transplanter for vegetable plug seedlings being capable of small labor load and evaluate its work performance under actual production conditions.

Material and methods

Design conditions

The fully automatic vegetable transplanter to be developed needs to meet these design conditions as follows:

— Seedling type: seedlings produced in the regular tray cells, the root system of each seedling intertwining together within the independent cell, plant height range from 50 mm to 200 mm, and the moisture content of the root lump remained at 60% ± 5.

— Plug tray: the injection molded polystyrene plastic trays, and 72 cells with the arrangement of 6 × 12, the cell dimensions of 45 mm height × 40 mm top.

— Substrate: the mixture of herbaceous peat, perlite, vermiculite and other agricultural materials in various volume proportions.

— Planting mode: two rows on one ridge, punching, and planting distance of 200 to 400 mm.

These requirements are determined based on the cultural practice for vegetable transplanting in China. Although the working speed seems to be in pursuit of high speed for many agricultural machineries, it is intended to concentrate a lot of efforts on making the function of the fully automatic transplanter more accurate and reliable. This transplanter is made to do precise planting of vegetable seedlings instead of skilled labors.

Development of fully automatic transplanter

The design plan of a riding-type fully automatic transplanter was proposed allowing continuous transplanting work on 2 rows with vegetable seedlings fed automatically. The prototype consists of a 4-wheel drive system, a seedling pick-up mechanism, a seedling feeding mechanism, a rotation discharging mechanism, a 2-row planting mechanisms, and a multi-source control unit (Fig. 1). The 4-wheel drive system of

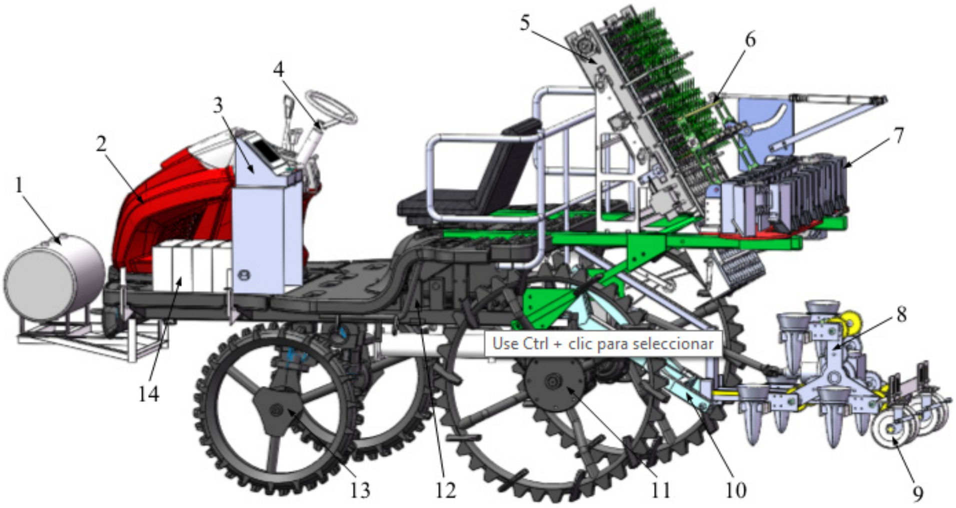

Figure 1. The structure schematics of the riding-type fully automatic transplanter: 1) air compressor; 2) engine; 3) control system; 4) operating system; 5) feeding mechanism; 6) pick-up mechanism; 7) rotation discharging mechanism; 8) planting mechanism; 9) soil covering ring; 10) hydraulic lifting mechanism; 11) driving wheel; 12) frame; 13) driven wheel; 14) battery.

the prototype was designed as driving based on the advanced chassis system of the high-speed rice transplanter. The seedling pick-up mechanism could extract several seedlings at a time from the tray cells conveyed by the feeding mechanism, and then transfer them to the rotation discharging mechanism where they would be released into the 2-row planting mechanisms. The planting mechanisms automatically transplanted the seedlings into the ground. The multi-source control unit was used to carry out the flexible automation of seedling transplanting.

Seedling pick-up mechanism

The function of the seedling pick-up mechanism is to auto-extract seedlings from the growing trays, transfer them, and release them. The seedling pick-up device may be divided into two major components of a path manipulator and a gripper. The path manipulator which looks like a robot arm is to generate an appropriate work trajectory of seedling extraction. When the gripper approaches a seedling, its direction should be normal to the cell surface for maximum extracting performance. In order to hold the seedling as firmly as possible, the path manipulator should be designed to move the pick–up pins deeply penetrate into the root soil of a cell in a straight line. At the discharge point, the gripper must be a little upward relative to the vertical to account for the inertia acting on the seedling. The gripper equated with a robot hand is to grasp seedlings within the tray cells, hold them and release them. At the pre-determined stations, the gripper should precisely extract and discharge seedlings. During the transfer from the extracting to the discharging points, seedlings should be held firmly.

A mechanism for the path manipulator was created through an innovative design of type-II mechanism combination in series (Fig. 2a). Its mechanical work principle is one of the mechanism combination in series consisting of an oscillating guide linkage mechanism (driving cylinder & rocker) and a grooved globoidal cam mechanism (connecting link & fixed groove). Specifically, the rocker, driven by the driving double-acting cylinder, can swing with an angle range. Meanwhile, the rocker is jointed with one end of the connecting link. The other end of the connecting link is constrained on the fixed globoidal groove. Thereby, the connecting link which is moved by the rocker copies the required work trajectory jointly under the constraint of the globoidal of the fixed groove.

In a work cycle of picking up seedlings, the conceptual working of the path manipulator is shown in Figs. 2a-2d. The driving double-acting cylinder pushes the rocker (from right to left in Fig. 2a) forward, and the connecting link moves outward along the left straight-line groove. The pick-up pins of the gripper approach a seedling in a cell and straightforward penetrate into its root soil. Meanwhile they squeezing the root soil gradually in the process of penetrating. As the pick-up pins hold the root soil of the seedling at their maximum penetration depth, the driving double-acting cylinder pulls the rocker back (from left to right in Fig. 2b). So

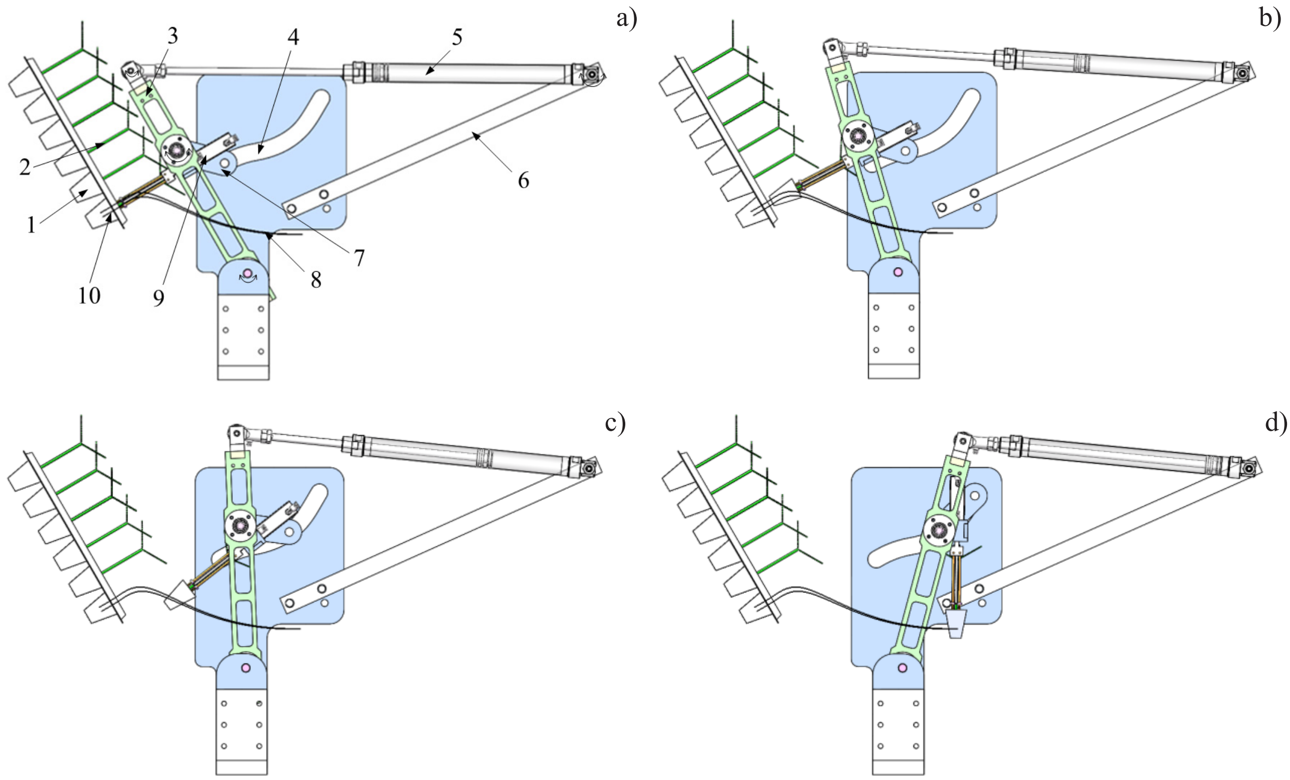

Figure 2. Conceptual working of the path manipulator: 1) plug tray; 2) plug seedling; 3) rocker; 4) fixed groove; 5) driving cylinder; 6) frame; 7) connecting link; 8) picking up trajectory; 9) gripper; 10) pick-up pins.

the connecting link moves back along the same straight-line groove. The gripper moved by the path manipulator extracts the seedling from the cell (Fig. 2b). The driving double-acting cylinder continues to pull the rocker back, and the connecting link moves along the circular-line groove. Then, the gripper is moved to adjust the attitude from its tilt to an upright position (Fig. 2c). When the driving double-acting cylinder pulls the rocker back to the right end, the connecting link again moves along another straight-line groove. Thereby, the seedling is kept as upright as possible and hovering in there, which is waiting for releasing (Fig. 2d). This completes a work cycle of approaching, penetrating, squeezing, extracting, transferring, and discharging a seedling.

The key point in designing the path manipulator is to form the appropriate globoidal of the fixed groove, which is used to create the seedling pick-up trajectory. According to the theory of mechanisms, the closed-loop vector equation of the path manipulator may be expressed, and its mathematical relationships between linkages groups would be established (Han *et al.*, 2015). Then, based on the structural and spatial layout of the pick-up device, the basic dimensions of the linkage group can be determined. As a series of the pin tips are planned, they combine into the working trajectory for seedling extraction. Finally, the central points of the appropriate globoidal of the fixed groove could be reversed with the numerical analytical method. Then after a rolling circle is added to the central points, the inner globoidal groove can be copied out with the envelope method. In order to avoid friction-induced heat and wear in the globoidal groove, self-aligning ball bearings may be considered as a type of slider motion. Thereby, the design of the path manipulator for seedling extraction was finished.

The gripper is a pincette-type mechanism using two swinging fingers and four pick-up pins (Fig. 3a). A cylinder is used to drive two swinging fingers closing and opening, which makes the pins squeeze the seedling gradually as they penetrate into the cell and then do the opposite when the seedling is discharged. The cylinder block was installed on the connecting link of the path manipulator. Two swinging fingers are symmetrically connected to the frame of the cylinder block via a hinge joint, and the four pick-up pins were half-and-half fixed onto the end of the two swinging fingers. The pins are ringed by the U-type pull rod fixed on the piston. As the U-type pull rod moves down and up, the pins may open and close, correspondingly. Meanwhile, the U-type pull rod may also push the seedling out of the pins during its downward movement.

At the start of a work cycle, the cylinder pushed the U-type pull rod forward, and the pick–up pins open as they approach a seedling in a cell (Fig. 3a).

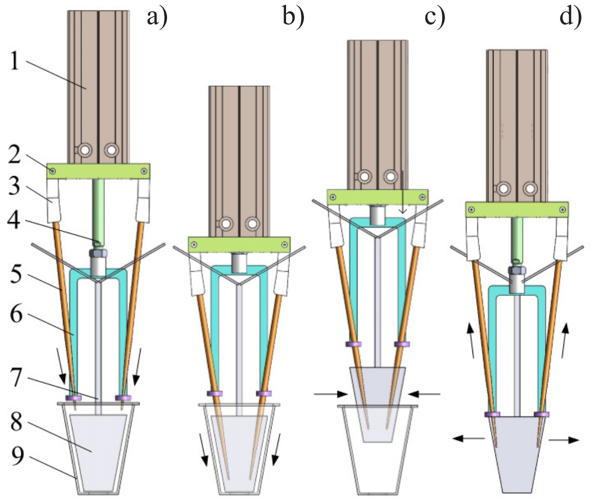

Figure 3. Operation of the gripper for seedling extraction: 1) cylinder block; 2) shaft; 3) swinging finger; 4) piston; 5) pick-up pins; 6) U-type pull rod; 7) seedling; 8) root soil; 9) tray cell.

As the gripper gradually approaches the seedling, the pick-up pins assembly penetrate into its root soil until the pins hold the soil of the seedling at their maximum penetration depth. Meanwhile, the pins squeeze the root soil gradually as the cylinder pulled the U-type pull rod backward (Fig. 3b). The gripper was moved away from the tray, and its pins extract the seedling from the cell (Fig. 3c). The U-type pull rod does not move again until the gripper reaches the discharge point. At the discharge point, the cylinder pushed the U-type pull rod forward. So the pick-up pins open. Meanwhile, the rod pushes the seedling down, and the pins retract gradually from the root soil. Finally, the seedling could be released (Fig. 3d).

The overall dimensions of the gripper were determined by the tray cell sizes and plant characteristics. Since the pick-up pins penetrate into the root soil within the tray cell for seedling extraction, it should be ensured that the pins grasp the maximum amount of root mass (Yang *et al.*, 1991; Choi *et al.*, 2002). Therefore, the pins were designed to keep open as largely as possible within the edges of the cells as the pins deeply penetrate into the root soil, and then grasp the maximum amount of root soil. The pick-up end of the pin was made of 304 stainless steel wire with 1.6 mm in diameter for a length of 40 mm with the minimum soil breakage (Mao *et al.*, 2014). To penetrate into the root lump easily, the tips of the pines were sharpened and heat-treated for strength. In order to increase the stiffness, the remaining part of the pins was made of rigid round wire 3 mm in diameter. Since the gripper with multiple fine pins was very likely to dispersedly grasp the maximum amount of root mass, the two pins of the two swinging fingers used a type of fork design (Han *et al.*, 2015). As a result, the gripper held the seedlings firmly to conquer the adhesion force between roots and cell walls. Since the U-type pull rod activates the pick-up pins to hold seedlings at the cells and then release them at the discharge point, this component must be changed for different types of seedlings. Besides, the inner space of the U-type pull rod should be designed to shelter the seedling plants to prevent damages from automatic extraction.

In order to efficiently pick up seedlings from the tray cells, a doorframe-type pick-up system equipped with several grippers was constructed (Fig. 4a). The two equal swing links connected by a crossbeam were configured as a swing door-frame. Several grippers in accordance with the tray cells were equipped in an array on the connecting crossbeam. At a work cycle, the seedling pick-up mechanism could pick up the entire row of seedlings at a time. So there is a reserve for seedling extraction, which could meet the requirements of high-speed planting. It was equal to several hand placements, which made that seedlings could be reliably picked up at a low speed.

Seedling feeding mechanism

The seedling feeding mechanism was designed to move the plug trays to the working space of multi grippers according to the extracting requirement (Fig. 4a). Considering the workspace of the cell interval, the whole row of grippers were designed to extract seedlings at regular intervals. So it is an alternating pattern for finishing the entire row of seedlings extracted from the cells. The seedling feeding mechanism consists of a pallet-type double-row chain transmission system for longitudinal feed, a cylinder shift unit for horizontal reciprocating movement and several photoelectric sensors. The trays were placed on the steel plate between the two chains, and their step transmission was driven by the beams fixed across the top of the two chains. Meanwhile, the trays were pressed and led by two side bars. The sensors were used to detect the front-edge of a source tray in the grippers working space. As a half of the entire row of seedlings are extracted at one time, the cylinder shift unit moves the trays to next interval cells for extracting seedlings at another time. After the entire row of seedlings is extracted, the conveyors are moved forward to place the next seedling-row into the working space. This seedling feeding procedure is repeated until all seedlings in the plug trays are picked up. According to the mechanical dynamics of trays conveying, the servo motor system was designed.

Rotation discharging mechanism

The function of the rotation discharging mechanism is to hold several seedlings extracted by the pick-up device at

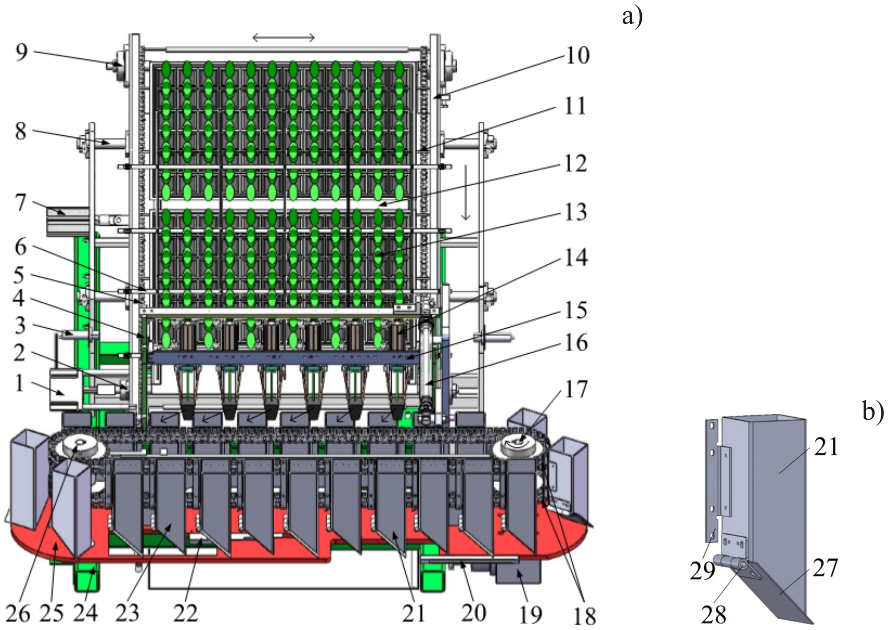

Figure 4. The structure schematics of the seedling feeding and rotation discharging mechanisms: 1) motor; 2 & 17) driving chain wheel; 3) photoelectric sensor; 4) rocker; 5 & 18) chain; 6) pressing trays rail; 7 & 16) cylinder; 8) slide bar; 9 & 26) driven chain wheel; 10) leading plate; 11) beam; 12) pallet; 13) plug seedling; 14) gripper; 15) crossbeam; 19) gear dividing box; 20) outer block beam; 21) outer opening hopper; 22) inner block beam; 23) inner opening hopper; 24) frame; 25) support plate; 27) end cover; 28) shaft; 29) connecting piece.

one side, transfer them flatly and discharge them again one by one into the 2-row planters at another side. It is a vertical rotating double-row chain transmission system (Fig. 4a). The driving chain wheel moves the driven chain wheel through the double-row chains suspended alternately with several outer and inner opening hoppers. In design, the hoppers were blocked by two kinds of the articulated end covers (Fig. 4b). The support plate props up the end covers making the hoppers hold seedlings in most places. The reasonable disconnected gaps were designed to abandon an activity of prop for the end covers which the hopper would be opened. So the seedling hold by the hopper could freely fall down. The opening position was depended on the planting requirements. A certain length of the block beam could be used to adjust the open operating point adapting two lines of planting distance. In design, the hoppers should smoothly catch the falling seedlings from the grippers and discharge them smoothly again. So the hoppers must be designed so large enough for accommodating the entire seedlings. Meanwhile, the arrangement of the hoppers need match that of the grippers for the sake of holding seedlings in order.

Seedling planting mechanism

Based on the requirements of the ridge cultivation, a planting mechanism with planetary gears of transplanting machine was designed (Hu *et al.*, 2013). It consists of a three-turning arm planetary gears mechanism, three cam mechanisms, and three duckbills (Fig. 5). The three-turning arm planetary gears mechanism was designed as the driving unit at the layout of 120 degree. The three duckbills were independently fixed on the outer planet gear. All of gears in the planetary gears mechanism have the same gear modules and numbers of teeth, which make the duckbills with a translational motion. The cam mechanism was used to move the duckbills open in the ground and close for holding the seedlings. For planting seedlings along two rows on one ridge, a pair of seedling planting mechanisms were constructed as the paralleling combinations adapting to the row spacing requirement. In design, the installation position of the planting duckbill could be neatly adjusted, which may meet different row spacing needs.

In theory, the motion of the planting duckbill is the translational motion with the three-turning arm planetary gears, and also following the machine moves forward. So a characteristic coefficient λ was introduced

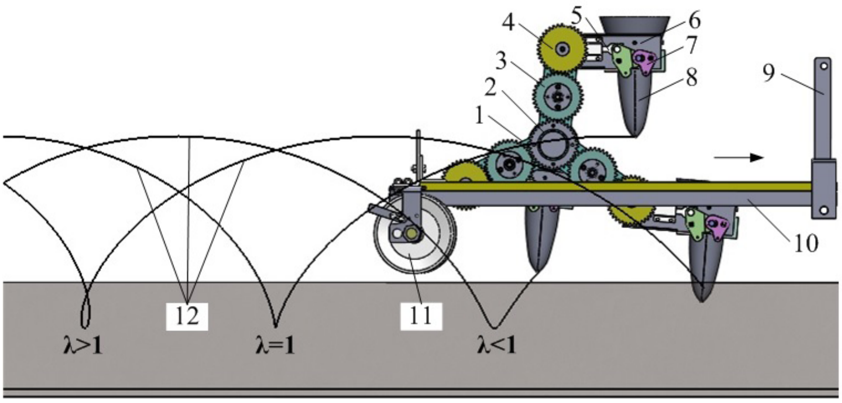

Figure 5. The structure schematics of the seedling planting mechanism: 1) planet carrier; 2) sun gear; 3) idle gear; 4) planet gear; 5) cam follower; 6) horizontal tumbler; 7) swinging link; 8) planting duckbill; 9) lifting mechanism; 10) frame; 11) soil covering ring; 12) planting trajectory.

reflecting planting mechanism end's motion trajectory, and it can be expressed as follows:

$$\lambda = \frac{R\omega}{V_t} \quad (1)$$

where R is the center distance from the sun gear to the planet gear, mm; ω is the angular velocity of the planet carrier, rad/s; V_t is the speed of the machine moves forward, mm/s.

As the structural design of the machine is certain, the different λ could be obtained through adjusting the angular velocity of the planet carrier and the speed of the machine moves forward (Hu *et al.*, 2013). The corresponding former and latter duck mouth ends' motion trajectory and the duck mouth's opening were formed (Fig. 5). As λ is less than or equal to 1, the planting trajectory is like the cycloid curve. In this case, the geometrical shapes of holes digged out by planting nozzle are rather large, and the seedlings are easily pushed over. As λ is greater than 1, the planting trajectory is like the trochid curve. The upright degree of seedling was the best in this case. Considering the soil backflow, the buckle point of the trochid curve was the most favorable position away from the ground for planting seedlings upright (Hu *et al.*, 2013). In specific applications, the angular velocity of the planet carrier and the speed of the machine moves forward need to be coordinated. The result is to create the right planting trajectory.

To further ensure planting quality, a soil covering ring could be configured for each seedling planting mechanism along the side of the seedlings. It could put down the soil around the seedlings planted, and earth up the seedling with soil in order to retain water for surviving. However, the soil covering ring could often not be used in planting with plastic film mulching. The reason is that the soil covering ring may scratch up the plastic mulch (Zhang *et al.*, 2013).

Control system

A PLC (Programmable Logic Controller) electric control system and a set of pneumatic circuit were designed for the flexible automation of seedling transplanting. As shown in Fig. 6, the electric control system is formed by the PLC, a touching screen, several sensors, a servo-driver unit, a relay unit, and some other connecting cables. A XC3-32E type PLC from Xinjie Electric Co., Ltd., Wuxi, China, was used as the control unit. It samples signals from the sensors, calculates, judges and executes the corresponding transplanting control actions. A user-friendly touching screen was designed to set some working parameters such as feeding speed & distance, operating time, start-stop control, and so on. The control operation of each working unit is coordinated by several sensors arranged the needed detection positions. Meanwhile, some movements and location information are fed into the control unit by the encoders and the position switches as a judge whether the corresponding action should be performed or not. The servo-driver unit was used to precisely drive the tray longitudinally to the grippers' working space according to the desired transplanting actions. In order to eliminate motion errors efficiently, S Shape Acceleration-Deceleration method was also adopted for the speed control process (Nguyen *et al.*, 2008). The relay unit connected to the output ports of PLC was to control cylinder solenoid valves.

The pneumatic circuits were designed using Fluid-SIM-P 3.6 software, as shown in Fig. 7. Compressed air after treatment with a filter regulator/lubricator combination was used to drive pneumatic execution

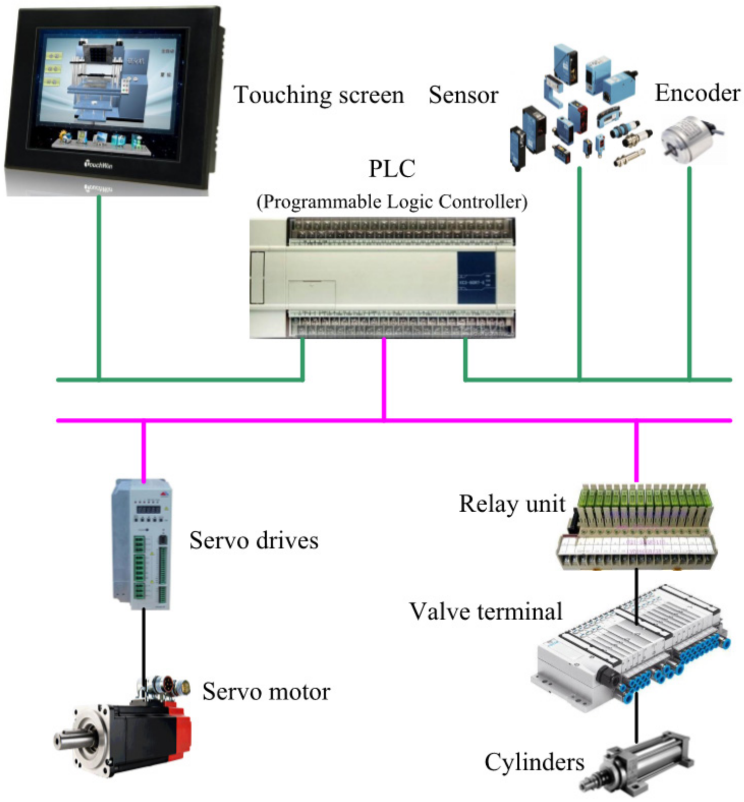

Figure 6. The structure of the electric control system for the fully automatic transplanter.

units. The double-acting cylinders labeled with A & B were used to drive the seedling pick-up mechanism swing for seedling extraction and move the trays reciprocating motion for alternately feeding seedlings. The double-acting cylinders labeled with C to H were to drive the swinging fingers closing and opening. The 5-port, 2-position solenoid control valves from DT0 (serial number of the D-type tamping solenoid control valve) to DT7 were designed to control the corresponding cylinders to finish multiple functions. The inlet way to each cylinder is constantly adjusted by the overflow-relieve valve in order to meet different working pressures of cylinders. In the circuits of the double-acting cylinder, the exhaust silencer throttle valve was installed on the solenoid control valve vent for adjusting the cylinder execution speed.

Trial produce and modification

A prototype of the fully automatic vegetable transplanter was constructed to examine whether its working efficacy was satisfactory or not. A 2ZG-6DK type 4-wheel drive system of the rice transplanter from FLW Agricultural Equipment Co., Ltd., Nantong, China, was modified as the chassis of the prototype. For the pneumatic automation, one power was diverted from the chassis engine to the air compressor. In addition, the chassis was adjusted to fit the ridge shape of vegetable planting. The two planting mechanisms were mounted on the chassis's hydraulic hang. The coordinated control between the rotation discharging mechanism and the planting mechanisms was attained by the chain drive. The seedling pick-up and feeding mechanisms were installed above the rotation discharging mechanism through the sensor detecting to realize the coordination with the rotation discharging and planting mechanisms. The PLC-based electric control system and the pneumatic circuit components were configured. According to the requirements of automatic transplanting of vegetable plug seedlings, the control software was programmed.

Firstly, the automatic pick-up system was test-operated to examine whether the functional requirements of extracting, transferring, and discharging a seedling, were satisfied. The testing seedlings were Jinyou cucumber marketable seedlings grown in 72-cell trays on a farm in Zhenjiang, Jiangsu Province, China. Seedling production was conducted to meet the Agricultural Professional Standard of China (General rule for vegetable plug transplants production: NY/T

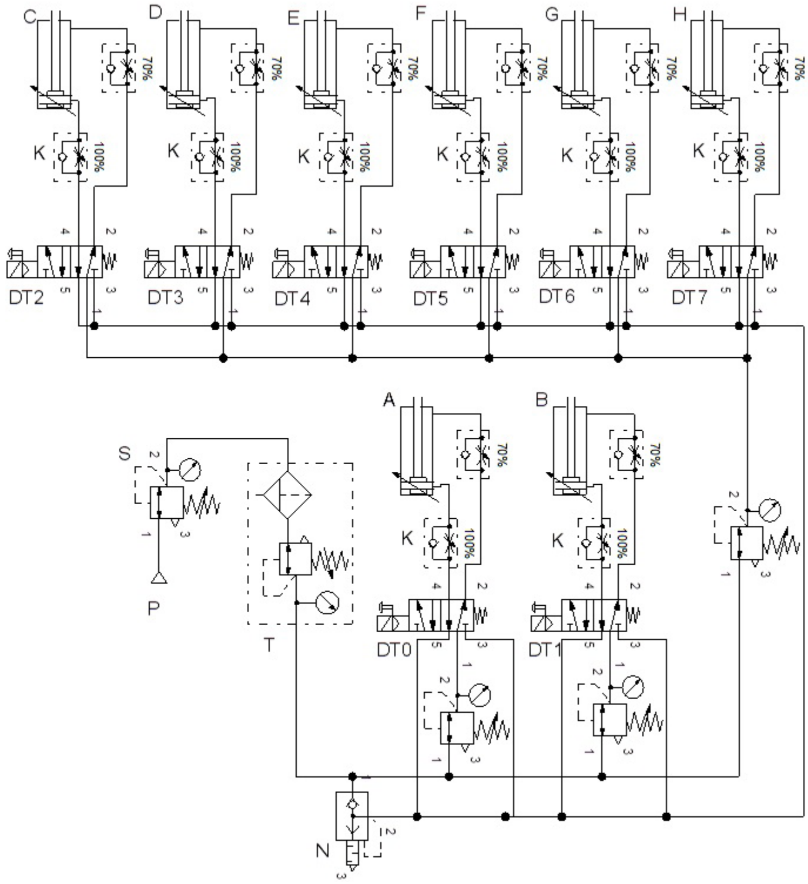

Figure 7. The schematics of the pneumatic circuit for the fully automatic transplanter: DT0-DT7, serial numbers of D-type tamping solenoid control valves; A-H, alphabetic numbers of the acting cylinders.

2119-2012). In testing, the transplanting process was observed and recorded on site using a high-speed video camera. Considering the vibration and the stability, there were different operating air pressures for various cylinders. By testing, when the operating air pressure of the driving cylinder was 0.35 Mpa at the cylinder diameter of 25 mm, it was easy to drive the entire row of grippers swinging for extracting seedlings. When the operating air pressure was 0.2 Mpa at the cylinder diameter of 15 mm, it was to smoothly drive the pick-up pins opening and closing for grasping the maximum amount of root soil. As the pin opening was at 35 mm, the maximum penetration depth at 33 mm, and the squeezing capacity at 10 mm, the grippers could completely extract the seedlings from the tray cells (Fig. 8a). By monitoring, it was found that the seedling trays were occasionally stuck in longitudinal feeding. The reason was that the entire tray was held on the leading plate so that the frictional resistance was quite large. When the entire rows of seedlings in extraction position were only held, it was easy that the trays were longitudinally fed. Further, the time sequence of the seedlings discharged from the grippers to the hoppers was compared. It was found that the discharging height difference made the seedlings not be accurately released into the hoppers. As the rotating hopper just approached the vertical central region of the gripper, the gripper pushed the seedling down and they could be accurately released into the hopper. For discharging seedlings, it needs some timing advance values to compensate for the freely-falling difference from the grippers to the hoppers.

Finally, the planting efficiency was tested. When the characteristic coefficient λ of the planting mechanism was set at 1.22, the former and latter duckbills in lifting would not touch the seedlings. It was done very well for avoiding to put down seedlings, and the upright degree of seedlings planted was also best. During planting seedlings, the planting mechanism is put down to the ground. That creates a gap between the rotating hopper and the planting duckbill. If the timing was not right, it was difficult to discharge seedling again into the planting duckbill. A leading tube was configured onto the transplanter, which could well connect the rotating

Figure 8. The riding-type fully automatic transplanter for vegetable plug seedlings.

hopper and the planting duckbill. The opportunity of seedlings discharged accurately for planting was increased. Since the used 4-wheel drive system has no ability to copy the ground, the seedlings may be planted with irregularity. In especial, the ridge surface was uneven with respect to the furrow. Through many trials, a pair of follow-up land wheels was configured to support the seedling planting mechanism preferably adapting the ground change (Fig. 8b). The planting uniformity was effectively improved. Finally, the modified prototype of the vegetable transplanter was developed, as shown in Fig. 8c.

Performance test

In order to evaluate the efficiency of the fully automatic transplanter, the performance tests of Spring planting in April 2018 were conducted on a vegetable base, Jiangsu Academy of Agricultural Sciences, Nanjing, China. The transplanting objects were solanaceous vegetable seedlings such as tomato (*Solanum lycopersicum* L.), pepper (*Capsicum annuum* L.) and cucumber (*Cucumis sativus* L.) seedlings. The used seedlings were for transplanting produced in the 72-cell trays by the local farmers. Their growth characteristics are presented in Table 1. The production pattern of transplanting was of planting seedlings along two rows on one ridge, and planting on the mulching plastic film. The planting spacing distance is set at 350 mm, 400 mm and 300 mm for tomato seedlings, pepper seedlings and cucumber seedlings, respectively. The transplanter was operated by two workers. One was for driving, and another for putting the trays on the seedling feeding unit. Other transplanting works were finished by the machine itself. The machine operation parameters were adjusted to the best. The transplanting rate was set at 60 plants per row per minute. Each test had five trays of seedlings transplanted continuously and the process was repeated 3 times. The corresponding results were recorded, and the data analyses were conducted.

Table 1. Growth characteristics of seedlings used in the performance tests.

Seedling	Seedling age, days	Moisture content, %	No. of leaves	*Plant height, mm	*Leaf length, mm	*Leaf width, mm
Tomato	33	58.94±2	5~6	113.15±5.86	38.14±4.68	24.07±4.32
Pepper	48	60.42±2	6~7	148.80±6.15	34.87±6.46	23.64±3.65
Cucumber	22	58.72±2	2~3	87.64±6.76	43.56±5.78	25.87±5.12

*Data are mean ± std. dev.

A success ratio in picking up seedlings (SR) represents how successfully the device performs extracting, transferring, and discharging of seedlings. It is determined as follows:

$$SR = \frac{N_{SF} - N_{MS} - N_{FF} - N_{SD} - N_{DF}}{N_{SF} - N_{MS}} \times 100\% \quad (2)$$

Where N_{SF} is the number of seedlings fed; N_{MS} is the number of missing seedlings; N_{FF} is the number of functional failures (seedling extraction failures; more than 1/4 of the root lump considered as a whole soil breakage); N_{SD} is the number of seedling damages (the stems torn by the pins); N_{DF} is the number of discharging failures.

According to the standard of the transplater of the dry field plant, some main planting performance indexes were investigated under actual production conditions.

A qualified percent of success in planting seedlings (Q) is determined as follows:

$$\begin{cases} Q = \dfrac{N_{HG}}{N'} \times 100\% \\ N_{HG} = N - (N_{MN} + N_{RN} + N_{LN} + N_{CN} + N_{EN} + N_{DN}) \\ N' = \text{int}(\dfrac{L}{X_r}) + 1 \end{cases} \quad (3)$$

where N_{HG} is the number of success in planting seedlings; N is the total number of planting seedlings; N_{MN} is the missed number of planting seedlings; N_{RN} is the repeated number of planting seedlings; N_{LN} is the laid number of planting seedlings (the included angle between the stem and the ground below 30º); N_{CN} is the covered number of planting seedlings; N_{EN} is the exposed number of planting seedlings; N_{DN} is the damaged number of planting seedlings (the stems torn by the pins); N' is the theoretical number of the test section; L is the length of the test section, cm; X_r is the theoretical plant spacing.

A coefficient of variation of plant spacing (CV) is determined as follows:

$$\begin{cases} CV = \dfrac{S_X}{\overline{X}} \times 100\% \\ S_X = \sqrt{\dfrac{1}{n-1}\sum_{i=1}^{n}(X_i - \overline{X})^2} \\ \overline{X} = \dfrac{\sum_{i=1}^{n} X_i}{n} \end{cases} \quad (4)$$

where S_X is the standard deviation of plant spacing, cm; $\overline{X}$ is the average value of plant spacing, cm; n is the number of seedlings tested; X_i is the qualified value of plant spacing, cm.

A qualified percent of planting depth (Q_{PD}) is determined as follows:

$$Q_{PD} = \frac{N_{PD}}{N} \times 100\% \quad (5)$$

where N_{PD} is the qualified number of planting depth; N is the total number of planting seedlings.

In testing, the success ratio in picking up seedlings was investigated for all the transplanted seedlings. Planting quality within 200 m was randomly selected for the qualified percent of success in planting seedlings and planting depth. This process was repeated 3 times, and the average results were recorded. Seedlings within 200 were randomly selected as the statistical analysis for the coefficient of variation of plant spacing.

Results and discussion

On the basis of the cultural practice for vegetable production in China, the riding-type fully automatic transplanter was developed being suitable for plug seedlings. The prototype enables continuous transplanting work on two rows simultaneously, a planting speed of 40-60 plants row^{-1} min^{-1}, with vegetable seedlings fed automatically. The transplanter was operated by two workers, one of who was for driving, and another for putting the trays on the seedling feeding unit. Other works of picking up seedlings, feeding, and planting, were finished by the machine itself. There is small labor load. The integrated technology of mechatronic, pneumatic and hydraulic systems engineering, was fully applied to the development of the fully automatic transplanter for the flexible automation. So the machine has a simple structure, and is also reliable. Besides, the automatic transplanting unit could be modularized as the paralleling combinations adapting to the multi-row planting requirements.

The results of the performance tests for automatically picking up seedlings are shown in Table 2. The success ratios were 94.11%, 93.86% and 93.78% for 33-day tomato seedlings, 48-day pepper seedlings and 22-day cucumber seedlings, respectively. Although much care was taken in producing the health and uniform seedlings, some empty cells and weak plants were

Table 2. Results of performance tests for automatically picking up seedlings.

Seedling	N_{SF}	N_{MS}	N_{FF}	N_{SD}	N_{DF}	SR, %
Tomato	1080	27	25	13	24	94.11
Pepper	1080	38	30	18	16	93.86
Cucumber	1080	19	6	32	28	93.78

N_{SF}, number of seedlings fed; N_{MS}, number of missing seedlings; N_{FF}, number of functional failures; N_{SD}, number of seedling damages; N_{DF}, number of discharging failures; SR, success ratio in picking up seedlings.

still present in the trays. To some extent, the empty cells and weak plants could definitely influence the effectiveness of transplanting operation. If the blank cells and unhealthy seedlings in the trays could be filled by another intelligent robotic transplanter, the automatic transplanting performance would be better (Yang *et al.*, 1991; Mao *et al.*, 2014). As the root soils of several seedlings were not well developed, the seedling extraction failures and soil breakage occurred in transplanting such as tomato seedlings and pepper seedlings with the maximum functional failures. To some extent, more fibrous growth media such as the rockwool and the moss peat was used to improve the root systems (Ting *et al.*, 1990). Since leaf damage has little effect on the later growth (Choi *et al.*, 2002), the stems torn by the pick-up pins were considered as seedling damages. Comparing the number of seedling damaged to the successful seedling extractions, it was found that the reason why the stems were torn by the pins was that some seedlings grew in the picking up position. It resulted in 13 tomato seedling damages, 18 pepper seedling damages and 32 cucumber seedling damages. To reduce gasping damages to seedlings, it is recommended that the plants should grow in the centre of the respective tray cells as much as possible (Shaw, 1993). It is particularly important for cucumber seedling automatic transplanting. Since the cucumber seedling stems are quite brittle, they may easily break as the pins penetrate into the root lumps during the process of picking up seedlings (Mao *et al.*, 2014). The cases for discharging failures occurred mainly when the leaves were tangled with the pins, and thus, the seedlings could not be removed off the pins easily. This fact confirms again that short and sturdy plants with root system well developed are more suitable for mechanized transplantation (Shaw, 1993; Han *et al.*, 2015; Kumi *et al.*, 2016). On the whole, the seedling pick-up device developed could extract the plants automatically by means of a system based on the doorframe-typed swinging grippers, whose diameters may vary depending on the holes on the lower part of the tray used. For a high-quality seedling extraction, the health and uniform seedlings should be produced for the high-efficiency transplanting mechanization.

The results of planting quality and planting accuracy of the fully automatic transplanter are shown in Tables 3 and 4. Viewed from the testing results, the qualified percent of success in planting seedlings were up to 92.87%, 91.23% and 93.00% for tomato seedlings, pepper seedlings and cucumber seedlings, respectively. The *CV* was 4.78%, 4.26% and 3.67%, which reflected the uniformity of planting seedlings. The planting depth could meet the agronomic requirements of vegetable production, and the qualified percent were up to 94.76%, 95.81% and 94.69% for three seedlings, respectively. For tomato seedlings, pepper seedlings and cucumber seedlings, the plants had not been completely extracted directly resulting in planting

Table 3. Results of planting quality of the fully automatic transplanter.

Particulars[1]	**Tomato**[2]			**Pepper**			**Cucumber**		
	L1	**L2**	**L3**	**L1**	**L2**	**L3**	**L1**	**L2**	**L3**
L, m	70	70	70	50	60	70	45	60	75
X_r, m	0.35	0.35	0.35	0.4	0.4	0.4	0.3	0.3	0.3
N'	201	201	201	126	151	176	151	201	251
N	198	196	195	123	149	172	148	195	246
N_{MN}	2	2	2	1	1	2	3	1	1
N_{RN}	3	2	1	2	1	1	1	3	1
N_{LN}	1	1	1	2	3	2	2	1	2
N_{CN}	2	1	1	1	1	1	1	2	1
N_{EN}	2	1	0	1	2	1	0	1	1
N_{DN}	3	2	2	3	3	2	2	2	2
N_{HG}	185	187	188	113	138	163	139	185	238
Q, %	92.04	93	93.53	89.68	91.39	93	92	92	95
Average, %		92.87			91.23			93.00	

[1]L, length of the test section; X_r, theoretical plant spacing; N', theoretical number of the test section; N, total number of planting seedlings; N_{CN}, covered number of planting seedlings; N_{DN}, damaged number of planting seedlings; N_{EN}, exposed number of planting seedlings; N_{MN}, missed number of planting seedlings; N_{RN}, repeated number of planting seedlings; N_{LN}, laid number of planting seedlings; N_{HG}, number of success in planting seedlings; Q, qualified percent of success in planting seedlings. [2]L1, L2 and L3 are the number of trials, respectively.

Table 4. Results of planting accuracy of the fully automatic transplanter.

Particulars		Tomato	Pepper	Cucumber
Plant spacing[1]	$\overline{X}$	34.6	39.8	29.7
	S_X	1.65	1.70	1.09
	CV, %	4.78	4.26	3.67
Planting depth[2]	N	187	165	171
	N_{PD}	177	158	162
	Q_{PD}, %	94.76	95.81	94.69

[1] $\overline{X}$, average value of plant spacing; S_X, standard deviation of plant spacing; CV, coefficient of variation of plant spacing. [2] N, total number of planting seedlings; N_{PD}, qualified number of planting depth; Q_{PD}, qualified percent of planting depth.

inaccuracy. From seedling extraction to planting, there were several links through the twists and turns. As the root lumps were seriously broken in extraction, it was difficult to transfer and discharge them. Then, missed plantings occurred. This case happened occasionally, but the subsequent transplanting links would be affected. Some specific monitoring abilities need to be strengthened for the fully automatic transplanter. Because of ridging evenly for planting, the soil became softening and its backflow in planting was very well (He *et al.*, 2016). The planting mechanisms commendably transplanted the seedlings into the ground. As using the machinery to plant seedlings, the plant spacing was well guaranteed. The total coefficient of variation of plant spacing was less than 5%. Since a pair of follow-up land wheels was used to support the seedling planting mechanism preferably adapting the ground change, the planting uniformity was effectively obtained. Through the actual production tests, the planting quality and planting accuracy of the fully automatic transplanter was consistent with the transplanting machinery standard. After automatic transplanting, the seedlings were watered. Later observations showed that all the seedlings were alive and growing. The fully automatic vegetable transplanter satisfactorily grasped seedlings from the trays, transferred them, discharged them, and planted them into the ground.

Compared with the 2ZBA-ZA type semi-automatic transplanter from Hualong Co., Qingzhou, China, the developed fully automatic transplanter is riding type, which need that one operator is for driving. The semi-automatic is walk-behind type, which needs one operator making the transplanter under control. Besides, the semi-automatic transplanter with two rows on one ridge requires two operators for manual feeding of one seedling cell after another. The fully automatic transplanter only needs one operator for putting the trays on the seedling feeding unit. By contrast, there is one less labor. Meanwhile, the long-term continuous operation for the fully automatic transplanter is also feasible without operators' work fatigue. Further, the maximum work efficiency of 0.24 ha h^{-1} for the fully automatic transplanter is almost twice than the semi-automatic one. Compared with the PF2R type fully automatic vegetable transplanter from Yanmar Machinery Co. Ltd., Wuxi, China, this developed transplanter requires the general levels of site preparation and the common plastic standard trays. It is better suitable for the actual production conditions. In design, the 4-wheel drive system for rice transplanting was only adaptively modified as the chassis of the prototype. So the use of the drive transfer gearbox was restricted with a few adjustments of planting distance. In future, a specialized chassis needs to be developed for the vegetable transplanter. Because of the variety of vegetables and their farming techniques, more performing tests are needed before the developed fully automatic transplanter is finalized. It is especially to carry out high-load continuous testing. This vegetable transplanter is a combination of mechanical, electrical and pneumatic technology, which requires someone with some expertise to operate it. Once in the market, some professional farmers need to be trained in daily operation and regular maintenance.

In conclusion, a riding-type fully automatic transplanter for vegetable plug seedlings was developed on the basis of cultural practice for vegetable production in China. The machine feeds vegetable seedlings automatically and enables continuous transplanting work on 2 rows simultaneously. The integrated technology of mechatronic, pneumatic and hydraulic systems engineering, was fully applied for the flexible automation of seedling transplanting. As the first prototype, the performance tests were conducted. The testing results showed that success ratio in picking up seedlings was up to 90%, and the planting efficiency could well meet the requirements of agronomy cultivation. It still needs to improve automatic transplanting of seedlings, both from horticultural and mechanical points of view.

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