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Design and experiment of a control system for sweet potato seedling-feeding and planting device based on a pre-treatment seedling belt

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Abstract

Although existing sweet potato transplanters require automatic seedling feeding instead of manual seedling feeding, this causes seedling leakage and low efficiency. In this work, a control system for automatic seedling feeding of sweet potatoes was designed based on a pre-treatment seedling belt. The system uses STM32 as the main controller and obtains the running speed of the machine through the encoder. The speed of the planting motor can be adjusted in real-time according to the running speed to keep the planting distance stable. The speed control model and linkage control strategy of seedling-feeding and planting motors are investigated to keep the system feeding frequency and planting frequency consistent under running speed changes. In order to verify the performance of this control system, a test bench was built, and some experiments were conducted. The test results show that the average error of seedling-feeding motor speed is 4.04%, and that of planting motor speed is 3.28%. At medium and low operating speed levels, the stability of the seedling-feeding mechanism is good, and the relative errors of automatic seedling-feeding operation are 7.8% and 5.1%, respectively. The variation coefficients of plant spacing were 9.34% and 7.42%, respectively, indicating that the system could meet the seedling-feeding and planting device control requirements based on the seedling belt and realise continuous automatic seedling feeding in the process of sweet potato seedling transplanting.

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Key words: Sweet potato seedlings; seedling belt; automatic transmission of seedlings; mechanised transplanting; control system.

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Introduction

Sweet potato is an annual or perennial herbaceous plant that originated in the Americas and is widely cultivated in more than 100 countries. It is an important food crop that provides a rich source of protein and can also be used as feed, industrial raw material, and new energy material (Raymundo *et al*., 2014). As a crop with drought resistance, infertile tolerance, and excellent yield potential, sweet potato is of great importance to many developing countries, especially in Asia and Africa (Fuglie, 2007). In terms of total production, sweet potato is one of the five most important food crops in developing countries. According to FAO data, the global planting area of sweet potato in 2019 reached 7768 kha, of which Asia was 2922 kha, accounting for 29.51% of the global planting area, second to Africa. In 2019, Asia produced 59.11 million tons of sweet potatoes, accounting for 64.38% of global production, and China is the world's largest producer of sweet potatoes, with a total output of 51.79 million tons, accounting for 56.4% of the world's total output (Zhao *et al*., 2021). However, according to the industry, the combined tillage and harvest mechanisation of sweet potato is only 26%, which is lower than other major food crops. Among them, the amount of labour used in transplanting exceeds 65% of the entire production chain, with high labour costs and intensity (Fan *et al*., 2018). With the shortage of labour and the increase of labour cost, the mechanised and intelligent transplanting technology of sweet potatoes is seriously lagging, which has become the main technical bottleneck limiting the modernised production of sweet potatoes.

Sweet potato transplants are mainly divided into bare seedlings and potted seedlings transplants (Wen *et al*., 2021). Among them, the automation degree of pot seedling transplanting is high, but the corresponding pot seedling production is needed, and the cost is high (Yang *et al*., 2018; Han *et al*., 2021). Therefore, with some exceptions, sweet potato transplanters mainly use bare seedlings and rarely use potted seedlings. Due to the difficulty of dividing bare seedlings, the mainstream is still manual planting or semi-automatic transplanting machinery. Research on transplanting machinery originated in developed countries and regions such as Europe, the United States, and Japan (Ratnayake and Balasoriya, 2013; Iqbal *et al*., 2021). In Europe and in the United States, the transplanting was mainly direct planting, relying on artificial seedling release (Mazzetto and Calcante, 2011; Khadatkar *et al*., 2018). For example, the Italian FERRARI F-MAX transplanter can complete up to 16 lines of transplant at one time.

Furthermore, some automatic transplanting equipment is mostly based on pot seedling as the service object, such as Belgium Agriplanter company 2SP-W type sweet potato pot seedling automatic transplanting machine, the overall planting frequency up to 26,000 plants per hour. In Japan, small-sized machinery such as self-propelled clip transplanting machines and traction riding artificial transplanting machines are mainly used (Nagasaka *et al*., 2004; Shiratsuchi *et al*., 2008). For example, the 2ZYZ-2 small-sized self-propelled transplanting machine produced by Yanmar, Japan, allows the transplanting angle and depth adjustment and completes the film transplanting operation. Moreover, it belongs to the transplanting machine with a relatively high degree of mechanisation, and there are similar machines in Kubota, Japan (Fukushima *et al*., 2010). Additionally, the PVH100 sweet potato tilt transplanting machine developed by Iseki in Japan can realise film transplanting and complete the oblique planting agronomic.

In contrast, the research on mechanical transplanting technology in China has been relatively slow for a long time (Yu *et al*., 2014; Hu *et al*., 2020; Li *et al*., 2021; Zhong *et al*., 2021). For example, in recent years, the national sweet potato industry technology system has cooperated with Fulaiwei Agricultural Equipment Co., Ltd., and improved the 2ZL-1 semi-automatic chain clamp planter based on the chain clamp tobacco transplanter. Hu *et al*. (2016) developed the 2ZGF-2 sweet potato combined planting machine, which can complete rotary tillage, ridge formation, crushing stubble, ditching, planting, pressing, and ridge trimming of two ridges sweet potato at one time. Xin *et al*. (2017) invented a simple-type potted seedling transplanting mechanism based on elliptical gears combined with a double-crank five-bar mechanism. Yang *et al*. (2020) designed a control system for a mini-automatic transplanting machine of plug seedlings. Shentu *et al*. (2019) designed a sweet potato planting mechanism based on a genetic a1gorithm, and the mathematical model and constraints of the planting mechanism were established to optimise the solution. On the other hand, the existing transplanters require manual feeding of seedlings during operation and use ground wheel drive to drive the transplanter, which in general lead to high labour intensity, poor plant spacing uniformity, and low overall efficiency.

Given the above problems, according to the agronomic requirements of sweet potato transplanting, this paper: i) proposes a sweet potato automatic seedling-feeding method based on a pretreatment seedling belt; ii) designs a seedling-feeding and planting device driven by an electric motor and used for sweet potato transplanting based on the seedling belt; and iii) designs a feeding and planting control system for sweet potato seedlings by concerning the electric drive control scheme widely used in modern agriculture. The motor speed is adjusted in real-time according to the operating speed and target plant distance to achieve orderly seedling feeding and stable plant distance.

Materials and methods

Transplanting agronomy of sweet potato seedling

Before the transplanting, the seed potato is used to grow seedlings in the seedling bed, and the stem tip is cut after a certain period of growth and then transported to the field for seedling (Vithu *et al*., 2019). Four types of transplanting are generally used for sweet potato planting: direct transplanting, diagonal transplanting, horizontal transplanting, and bottom-type transplanting (Figure 1). In addition, there are two types of transplanting: film covered and without film covered. The device and system proposed in this paper are mainly applied to filmless mulching.

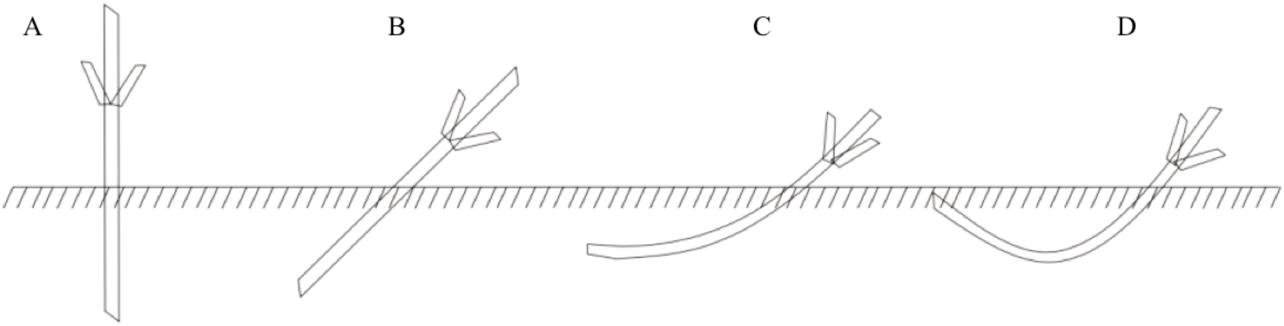

Figure 1. Method of planting sweet potato: direct transplanting (A), diagonal transplanting (B), horizontal transplanting (C), and bottom-type transplanting (D).

Automatic seedling -feeding method based on pre-treatment seedling belt

An automatic and orderly supply of seedlings is a prerequisite for the automatic operation of transplanting machinery. Since there is no reliable automatic seedling sorting method, the pre-treatment seedling belt is designed to avoid the need for continuous manual seedling sorting and feeding during the planting process. Before the operation, seedlings are fixed evenly on the band. An automatic and continuous seedling supply is achieved by a quick change of the seedling band, similar to a rice transplanter's seedling tray.

The pre-treatment seedling belt is composed of two cohesive buckles (Figure 2). The adhesive layer of the buckle is aligned with the two long edges of the buckle respectively in a strip, and the width is smaller than the width of the buckle so that the buckle is partially bonded, and this can reduce the adhesive force of the two buckles and ensure the smooth separation of the two buckles. The grooves are arranged on the adhesive layer of the buckle so that the grooves are convenient for the fixation of a single seedling. The seedlings can be pre-treated and fixed using the buckle so that the seedlings can be arranged and fixed orderly, and the seedling belt can be rolled up to form a seedling belt plate.

Design of automatic seedling-feeding device for sweet potato

The seedlings feeding and planting device is shown in Figure 3. The pre-treatment seedling belt is installed on the mechanism at first. In the process of planting, the rolling wheel of the left and right sides rotates in the opposite direction, driven by the seedling-feeding motor so that the seedling moves longitudinally with the seedling belt under the guidance of the guiding wheel and is clamped by double flexible discs apparatus, to complete the seedling-feeding action. The flexible disc rotates under the drive of the planting motor and holds the seedlings to the ground for transportation. When the seedlings reach the release point, they will fall into the planting ditch under the action of gravity to complete the planting action.

Design of seedling planting control system

The technical goal of the system is to control the motor speed in real-time according to the preset target spacing and the driving speed of the tractor to realise automatic and orderly seedling feeding and continuous and stable planting. During the system's operation, the encoders on the wheels and the motor respectively collect the operating speed of the machine and the motor speed, which

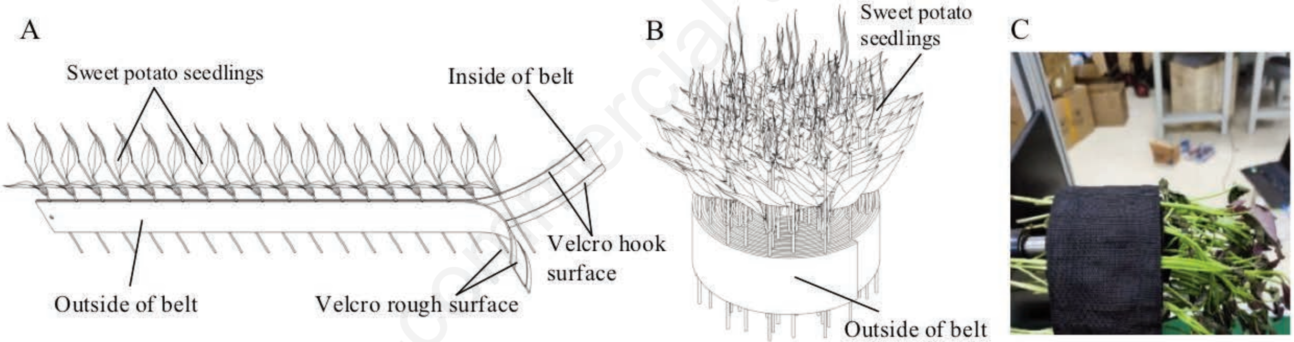

Figure 2. Schematic diagram of sweet potato seedling pre-treatment: pre-treatment seedling belt (A), overall effect (B), and physical seedling belt (C).

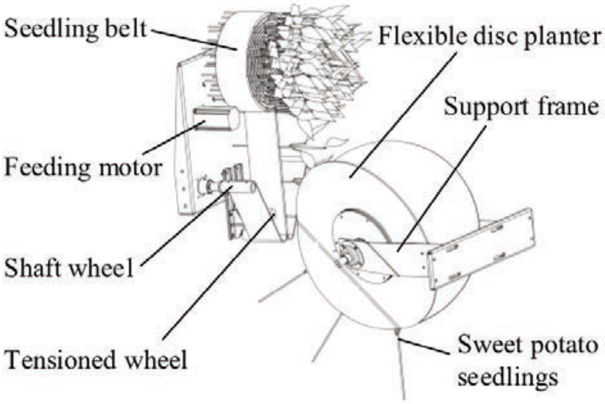

Figure 3. Structure diagram of seedling-feeding and planting device.

are used as the input signals of the controller. The controller outputs the control signal to make the motor rotate according to the target speed, which drives the seedling-feeding and the planting mechanism, respectively. The system is a closed-loop control system that takes the seedling planting controller as the core, the operating speed signal as the control basis, and the stepper motor as the actuator. Its working principle is shown in Figure 4.

In order to adjust the speed of seedling-feeding and planting motor in real-time according to the change of tractor forward speed and keep the frequency of seedling feeding and planting consistent, and the planting spacing meets the agronomic requirements, the dynamic speed control model of seedling-feeding and planting motor has to be established. Furthermore, the working principle and the coordinated control of seedling-feeding and planting mechanism have to be studied to realise the linkage control of seedling-feeding and planting motor based on operation speed.

According to the working principle of the system, the operating process of the seedling planting device is shown in Figure 5A.

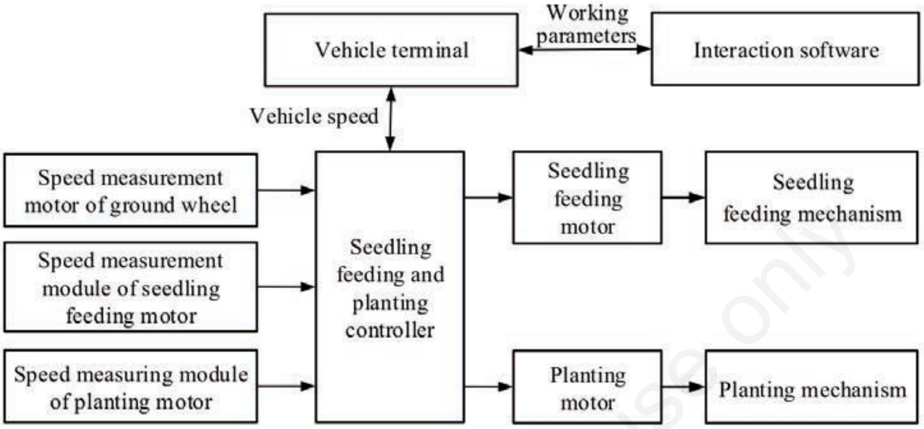

Figure 4. Schematic diagram of the control system.

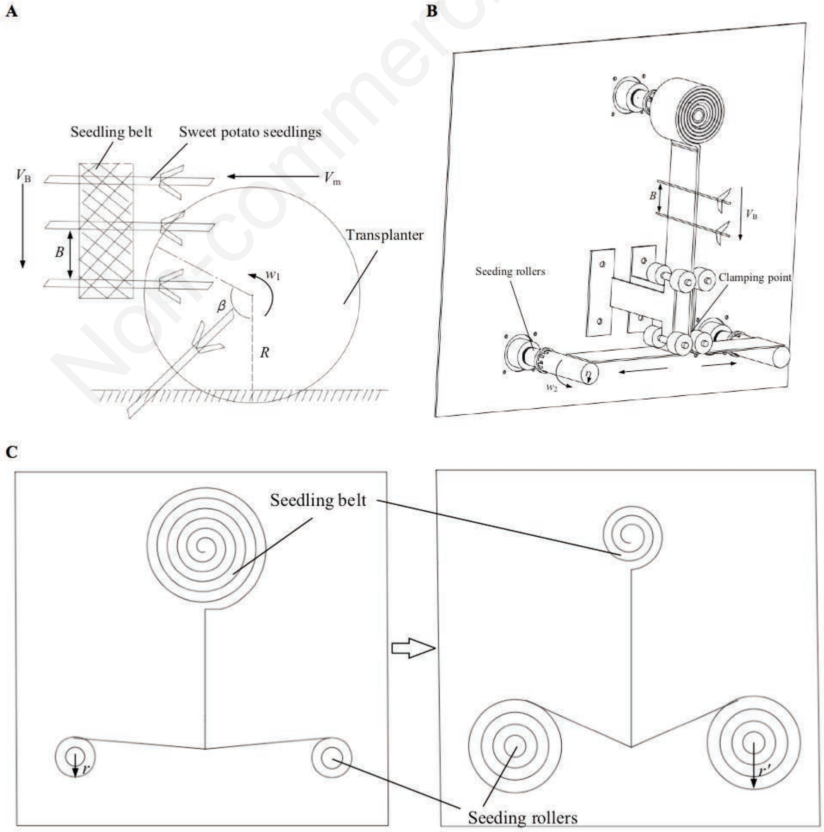

Figure 5. A) Schematic diagram of the planting process; B) schematic diagram of the feeding process; C) schematic diagram of the operating radius of the seedling motor.

Seedling-feeding and planting device are carried out under the tractor's traction. The seedling-feeding motor drives the seedling-feeding mechanism to transport seedlings to the planting mechanism. The planting motor drives the flexible disc planting device to carry out the seedling clamping and releasing operation.

When the mechanical parameters such as the radius of the flexible disc have been determined, the relationship between planting spacing X, planting frequency f, and operating speed V_m can be determined by the Eq. (1):

$$f = \frac{V_m}{X} \times 60 \tag{1}$$

The flexible disc rotates under the drive of the planting motor to make the circular motion for the clamping and putting of the seedlings. Within the effective clamping angle, the number of seedlings that can be clamped at the same time and can be set to N, so the relationship between the planting frequency f, the number of seedlings N, the clamping angle β, and the angular velocity w_1 and the planting motor speed n_1 can be determined by the Eq. (2) and (3) respectively:

$$w_1 = \frac{n_1 \cdot \pi}{30} = \frac{\beta \cdot f}{60 \times N} \tag{2}$$

$$n_1 = \frac{\beta \cdot f}{2 \times \pi \cdot N} \tag{3}$$

The theoretical speed regulation model of the plant motor is obtained by substituting Eq. (1) into Eq. (3), which then can be determined by Eq. (4)

$$n_1 = \frac{\beta \cdot V_m}{2 \times \pi \cdot N \cdot X} \times 60 \tag{4}$$

According to the working principle of the seedling-feeding mechanism, driven by the seedling-feeding motor, the seedling rollers on both sides rotate to the left and right to separate the seedling belt, and the seedlings are fixed on the seedling belt and move vertically downward. After reaching the clamping point, they are clamped by a flexible disc to complete the seedling-feeding operation. The operation process is shown in Figure 5B.

In order to ensure the accurate coordination of the seedling-feeding and planting process, the frequency of seedling feeding should be consistent with the planting frequency, which means that the time of single seedling feeding should be equal to that of single planting. The vertical running speed of the seedling belt is set as V_B, and the interval between two adjacent seedlings on the seedling belt is B. Therefore, the relationship between them can be determined by Eq. (5):

$$\frac{B}{V_B} = \frac{X}{V_m} \tag{5}$$

Because the speed of the seedling belt is equal to the linear speed of seedling roller rotation, therefore the vertical running speed of the seedling belt can be determined by Eq. (6), n_2 is the speed of the seedling-feeding motor:

$$V_B = 2 \times \pi \cdot r \cdot \frac{n_2}{60} \tag{6}$$

By substituting formula (5) into formula (6), it can be concluded that the relationship between the speed of the seedling-feeding motor and the operating speed by the Eq. (7):

$$n_2 = \frac{V_m \cdot B}{2 \times \pi \cdot r \cdot X} \times 60 \tag{7}$$

As shown in Figure 5C, with the continuous feeding of the seedling belt, the seedling belt around the rolling wheel increases, resulting in the equivalent operating radius of the seedling-feeding motor increasing gradually from the initial value r to r'.

According to Eq. (7), the change of equivalent operating radius r will affect the speed of the seedling-feeding motor, so the theoretical speed n_2 of the seedling-feeding motor needs to consider the change of operating radius in addition to the influence of V_m. Under ideal conditions, it can be considered that the radius increased by the rotation of the rolling wheel is equal to the thickness h of the seedling belt around it. In order to control the rotation speed of the seedling-feeding motor with the gradual increase of the equivalent operating radius to maintain the seedling-feeding and planting action at the same frequency, the system uses an optical encoder as the speed sensor of the motor, which is used to feedback the speed of the motor and record the number of rotation cycles j of the seedling-feeding motor. The relationship between the number of rotation rings and the equivalent operating radius of the seedling-feeding motor is shown in Eq. (8). When the seedling-feeding motor rotates a circle, a circle of the seedling belt will cover the rolling wheel, and the equivalent operating radius of the motor will increase h.

$$r' = r + h \times j \tag{8}$$

The seedling-feeding controller adjusts the speed of the seedling-feeding motor by capturing the encoder pulse to record the number of turns j around the seedling wheel. According to Eq. (7) and Eq. (8), the n_2 speed variation of the seedling-feeding motor with the number of turns j is obtained and can be determined by Eq. (9):

$$n_2 = \frac{V_m \cdot B}{2 \times \pi \cdot X \cdot (r + h \cdot j)} \times 60 \tag{9}$$

In order to control the two motors to adjust the speed in real-time according to the operation speed, the linkage control strategy of seedling-feeding and planting motor based on the operation speed is designed. The control process is shown in Figure 6.

Firstly, the current operating speed V_m of the machine is obtained by the ground wheel speed measuring unit, and the speed difference before and after is obtained by comparing it with the previous operating speed V_0. If the speed difference exceeds the threshold Y, the speed of the two motors is adjusted according to the motor speed control model; otherwise, the current speed is maintained, and the current operating speed is saved for the next cycle. When the number of rotation cycles is detected to increase, the speed regulation of the seedling-feeding motor is carried out separately. If the current operating speed is 0, the motor stops operating.

Hardware designs of control system

According to the working principle of the control system, the seedling-planting controller is the core hardware of the control system. The main functions include: collecting the pulse signal of the speed encoder to calculate the forward speed and the motor speed and monitoring the number of rotation rings of the seedling motor. The vehicle display terminal communicates the target parameters and sends real-time operational data to the vehicle terminal. Calculate motor speed and send motor control signal according to machine speed and target spacing.

In order to achieve the above requirements, this paper designs a seedling-feeding controller based on the STM32F407VGT6 microprocessor of STMicroelectronics (ST) Company. The core of the STM32F4 series microprocessor is ARM Cortex-M4, which has high performance, low power consumption, and low cost. As shown in Figure 7, a two-layer printed circuit board of 100×100 mm for the controller circuit board can meet the control requirements in the field working environment. The main performance parameters are shown in Table 1.

This paper adopts the Xinhan VMC1000 vehicle-mounted display terminal as the operating platform of the human-computer interaction software, which mainly realises the functions of setting the operating parameters such as the target plant distance of the system and displaying the operating information such as running speed, motor speed and sowing frequency in real-time. In order to achieve accurate speed measurement, the encoder model selected for the ground wheel speed measurement device and motor speed feedback is the Omron E6HZ-CWZ6C600P/R incremental encoder with 600 pulses per revolution of the motor shaft. The controller calculates the motor's actual speed by the number of pulses received per second. According to the characteristics of the low theoretical operating speed of the seedling-feeding and planting device, the iHSS57 integrated step servo motor of Jimeikang electro-mechanical is selected as the driving unit of the seedling-

Table 1. Test results of seedling operation.

Item	Parameter
Controller size	100×100 mm
PCB scale	Two-layer
CPU	STM32F407VGT6, LQFP-100
Maximum computing speed	168 MHz
RAM size	192 KB
ROM size	1 MB
Input voltage	DC 9-28 V
Communication mode	RS-232, RS-485
Motor drive function	4 - way unidirectional output
Working stability range	–40°C, ~85°C

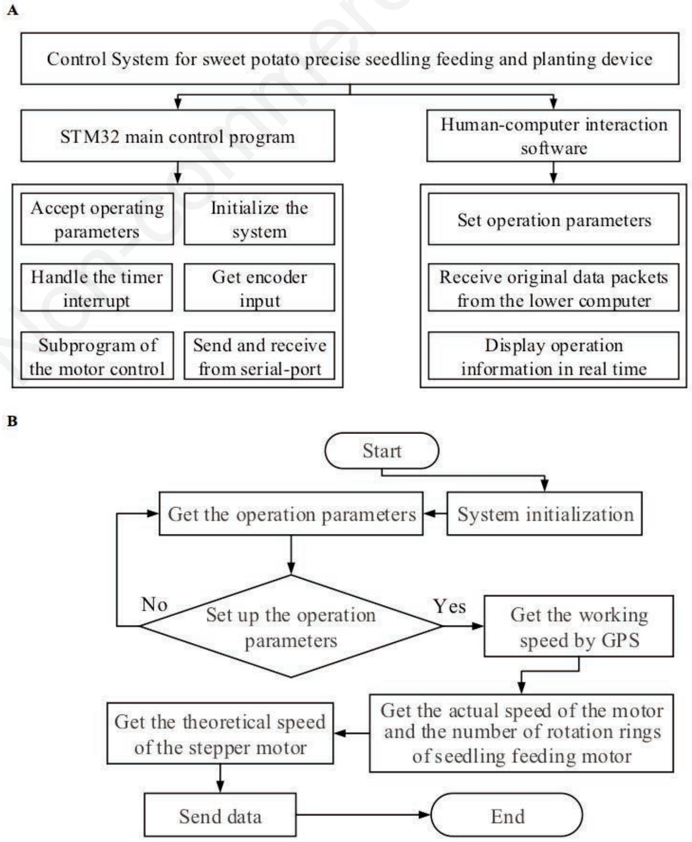

Figure 6. Strategies for motor coordinated work control.

feeding and planting mechanism. The minimum operating speed of the motor can reach 0.1 rps, which has the advantages of no step loss, high-speed response, and large driving torque.

Software designs of control system

As shown in Figure 8A, the software of this control system includes two parts: human-computer interface software and the main control programme of seedling-feeding and planting controller. The human-computer interaction programme was based on VS2010 development, using C++ language programming. The main control programme is developed based on Keil Vision 5 and programmed in C language.

To facilitate system operation and data interaction, the human-computer interaction interface is designed. According to the overall structure and function distribution of the software of the seedling-feeding and planting control system of sweet potato, the human-computer interaction software of the upper computer mainly includes the following three functions: parameter setting function, the original data packet receiving function of a lower computer, and the real-time display function of job information.

Users can input operation parameters such as target spacing through the interactive interface. The interactive software receives the data transmitted by the controller and displays the machine's current moving speed and planting frequency in real-time. After setting the job parameters, click the start button, and the software sends the job parameters to the controller and receives the data sent by the display controller in real-time.

The primary function of the main control programme is to analyse and process the information from each unit, such as human-computer interaction software and encoder speed measurement module and output the control signal of the motor according to the user's operating requirements and current operating speed. The overall process is shown in Figure 8B.

Firstly, the I/O ports, serial port, and controller timer are initially configured. Then, the timer interrupt is entered to obtain the operation parameters, and the data communication between the HCI software and the controller is verified to determine whether the operation parameters are set. After the transplanting operation starts, the input pulse of each encoder is collected by the input capture function of the STM32 timer to calculate the operation speed, the motor's actual speed, and the number of revolutions of the seedling-feeding motor is monitored. The theoretical speed of the stepper motor is calculated according to the target plant distance and the current operating speed. The motor's actual and operating speeds are sent to the display terminal through the serial port for real-time display. The motor speed is adjusted in real-time according to the deviation of the actual speed of the stepper motor from the calculated theoretical speed to realise the closed-loop control of the system and ensure the stability of the transplanting plant distance when the driving speed of the tractor changes.

Test bench

In order to verify the accuracy and stability of the control system, a test bench was built to carry out the motor speed control accuracy, automatic seedling-feeding mechanism performance, and seedling planting accuracy.

The Xushu 27, a common variety of sweet potato, was selected as the test material, with an average length of 28 cm and a diameter of 4 mm. The test bench is shown in Figure 9A. It is equipped with a conveyor belt driven by a variable frequency motor; it can adjust speed to simulate the ground. The speed range of the conveyor belt is 0-0.5 $m \cdot s^{-1}$, the speed of the transplanter. The feeding mechanism, planting mechanism, and simulated ground adjusted the space positions among each other according to the working condi-

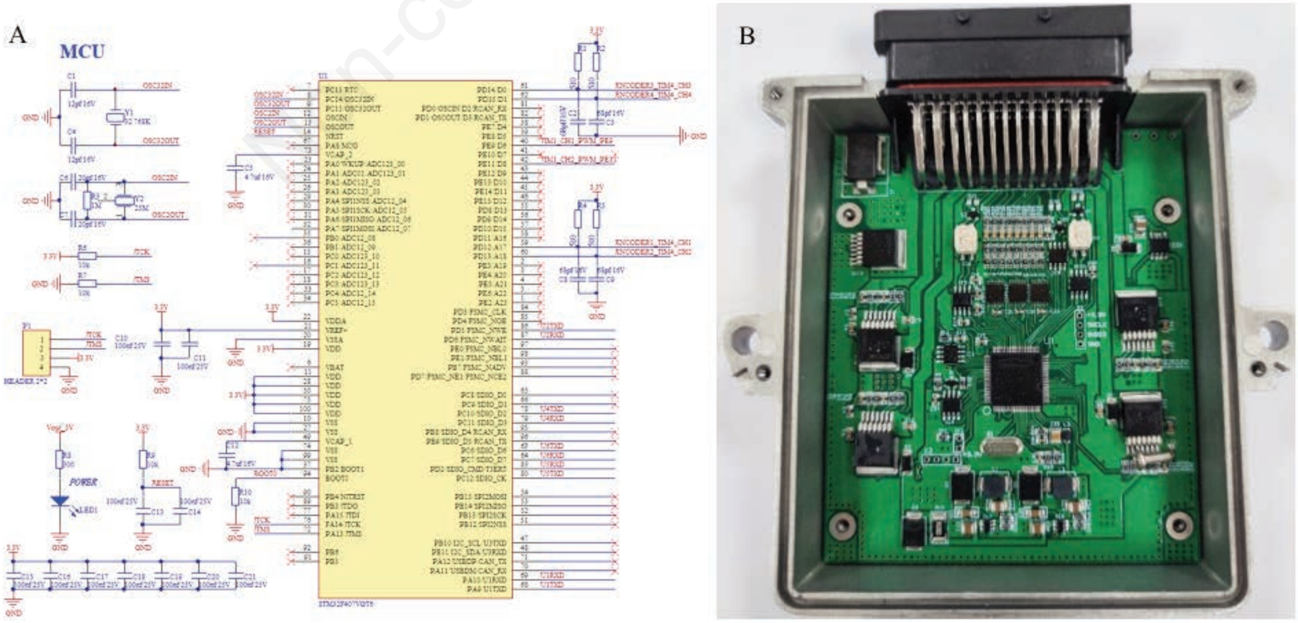

Figure 7. Feeding planting controller hardware: schematic diagram of the controller (A) and control system core module (B).

tions. The variable-frequency motor adopts the 5IK120RGU - CFAC induction motor of Ningbo Zhongda Motor. The rated working voltage was 220V, the rated power was 120W, and the maximum speed was 1350 rpm addition, the ground wheel speed encoder was installed on the conveyor belt to provide feedback on the operation speed. The control accuracy of the motor's control system directly affects the device's performance. In order to test the system's control accuracy of the motor speed, the operating speed on the bench was changed. The target plant spacing was set to 25 cm. The operating speed of the simulation machine fluctuated between 0.2 m·s^{-1} and 0.4 m·s^{-1}, and the control system adjusted the rotational speed of the motor in real-time according to the operating speed. The controller collects the actual speed of the seed feed and seeding motors in real-time and sends the data to a laptop for processing.

In order to verify the accuracy of continuous seedling-feeding operation, the performance test of the seedling-feeding mechanism was carried out on the test bench (Figure 9B and C). The theoretical planting spacing was set as 25 cm, and the spacing between seedlings in the belt was controlled as 10 cm. The operating speed was set to 0.2, 0.3, and 0.4 m·s^{-1}, respectively. Thirty seedlings per test were used. The seedlings dropped evenly from the seedling belt and fell on the conveyor belt. The spacing between the seedlings dropped, it was manually measured as the actual value and the theoretical value for comparing 10 cm spacing between the seedlings.

To verify the accuracy and stability of the system in controlling the plant spacing at different operating speeds, the accuracy of the planting spacing was tested on a test stand (Figure 9C). The theoretical plant spacing was chosen as 25 cm according to the agronomic transplant requirements. The operating speeds of the selected system were 0.2, 0.3, and 0.4 m·s^{-1}, respectively, due to the low operating speed of mechanical transplanting of seedlings, which is usually powered by a tractor with track gears. As shown in Figure 9C, the seedlings fell on the running conveyor belt after feeding and planting on the test bench. The distance between the centre points of two adjacent seedlings falling on the conveyor belt on the same parallel line was taken as the actual plant distance. The spacing of seedlings on the conveyor belt was measured manually. The experiment was repeated three times simultaneously, and 30 plant spacing was measured each time. The test data were recorded and analysed according to the planting accuracy index in JB/T10291-2013 Dryland planting machinery standards. In this experiment, the standard deviation (SX) and the coefficient of variation (CVX) were selected to evaluate the accuracy and uniformity of the operating performance of the system, and the planting frequency of the system was calculated as a reference.

Results

Motor speed control accuracy test

The rotational speed response curve was obtained by comparing the actual speed with the target speed in the 60s, as shown in Figure 10.

As shown in Figure 10, during the operation of this system, the motor speed responds quickly to the running speed under the con-

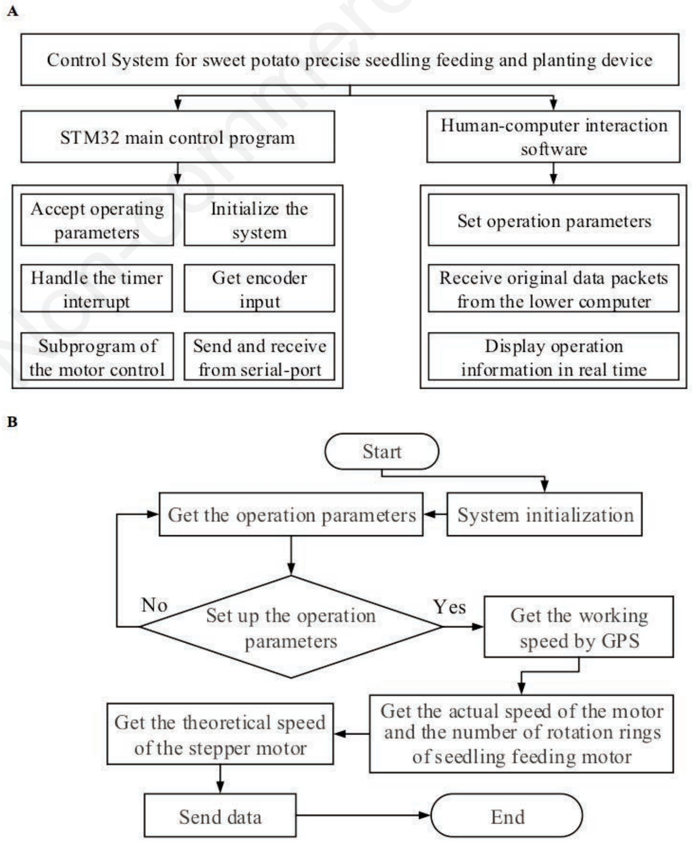

Figure 8. A) Software framework of the control system; B) flow chart of the main control program.

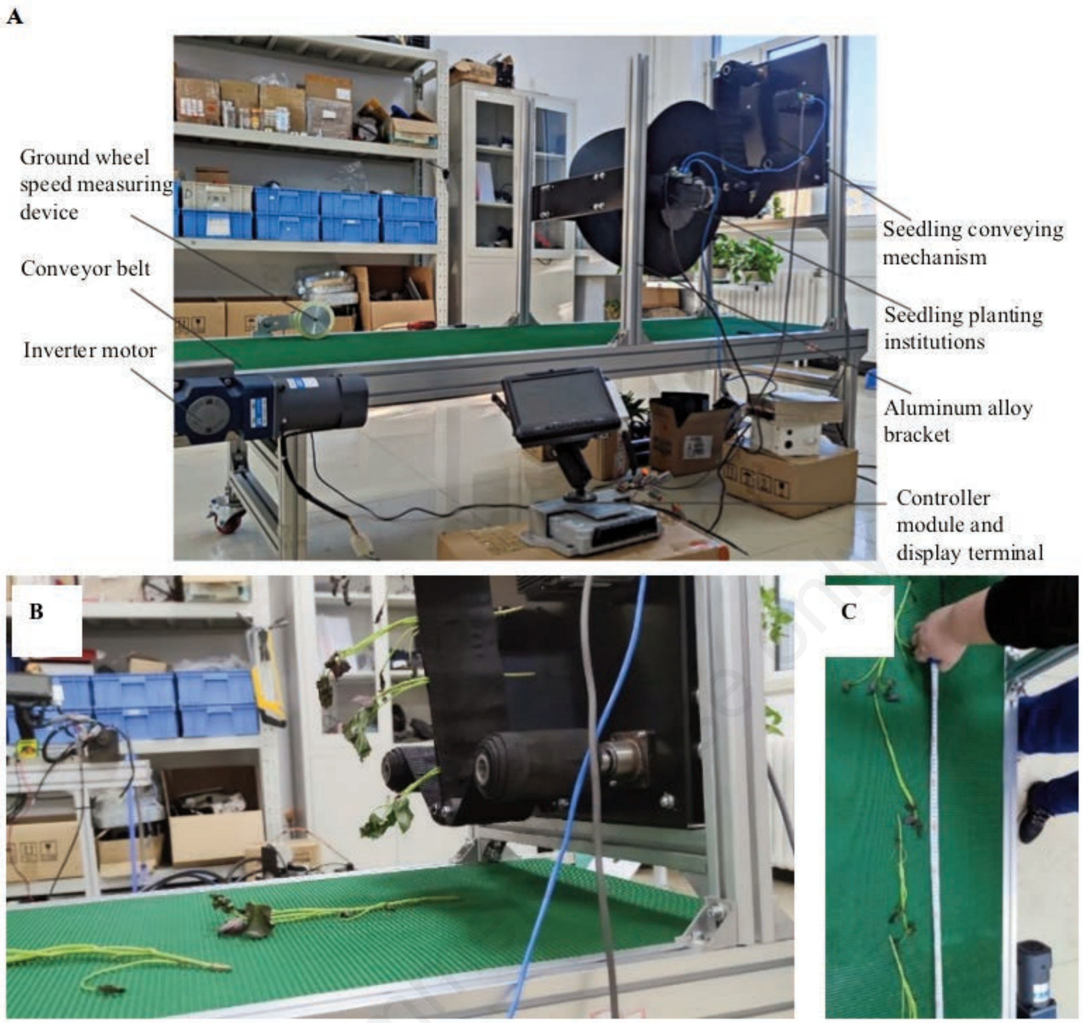

Figure 9. Test platform (A); automatic seedling delivery performance test: test process (B) and data acquisition (C).

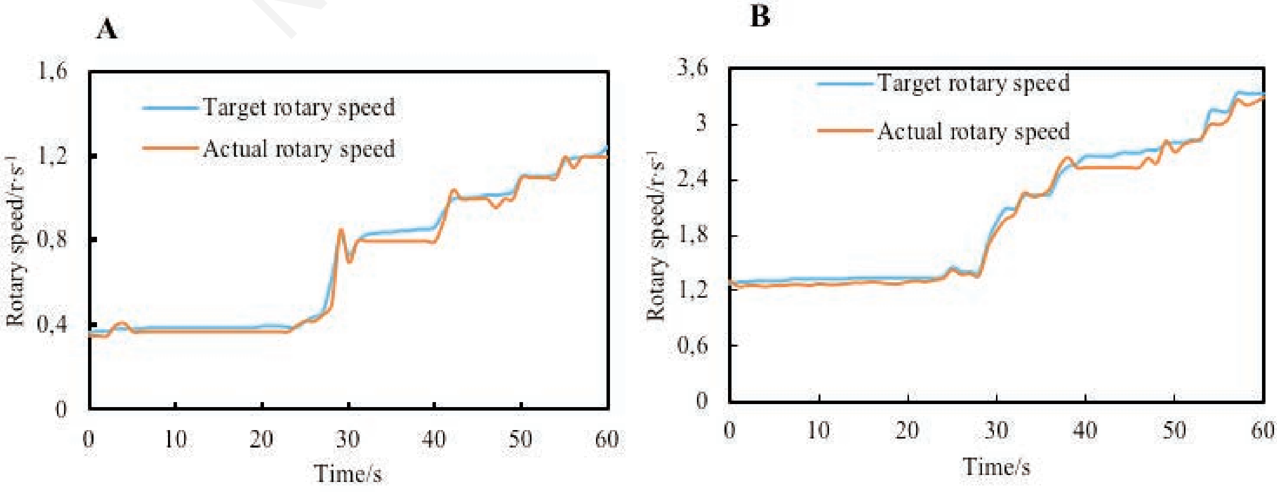

Figure 10. Results of motor speed response curve control accuracy test: seedling-feeding motor (A) and planting motor (B).

Table 2. Test results of seedling operation.

Operating speed/m · s^{-1}	0.2	0.3	0.4
Average spacing/cm	10.51	10.78	11.14
Minimum/cm	9.40	8.44	8.15
Maximum value/cm	11.5	11.8	12.4
Standard deviation/cm	0.63	0.82	0.95
Relative error/%	5.1	7.8	11.4

Table 3. Analysis of planting accuracy test results.

Operating speed/m · s^{-1}	0.2	0.3	0.4
Standard deviation of plant spacing/%	1.90	2.22	4.05
Coefficient of variation of plant spacing/%	7.42	9.34	13.29
Planting frequency/min^{-1}	48	72	96

trol program, and the motor's actual speed is consistent with the target speed. Therefore, by calculating and processing the errors of target speed and actual speed, the average error of feeding motor speed is 4.04%, and the average error of planting motor speed is 3.28%, which indicates that the accuracy and stability of both feeding and planting motors are good and can meet the needs of normal planting operation.

Performance test of seedling-feeding mechanism

The test results are shown in Table 2. It can be seen from Table 2 that the average seedling spacing under three operating speeds is 10.31, 10.53, and 11.14 cm, respectively, and the accuracy of seedling feeding is high. The relative errors at the operating speed levels of 0.2 and 0.3 m•s^{-1} were 5.1% and 7.8%, respectively, with good stability.

Experiment on planting precision of seedlings

The test results are shown in Table 3. Under the three operating speeds, the S_X of the three repeated tests were 1.9 cm, 2.22 cm, and 4.05 cm, and the CV_X were 7.42 %, 9.34 %, and 13.29 %, respectively. It can be seen that as the planting frequency increases, the CV_X is rising, indicating that the stability of plant spacing is getting worse. In the operating speed range of 0.2-0.3 m•s^{-1}, the CV_X of the system was lower than 10%, and the S_X was low too. It indicates that the operation process of the control system is stable at medium and low speeds, which can meet the operating requirements of the transplanting. Considering the control precision of planting spacing and planting frequency, it can be concluded that when the operating speed is 0.3 m•s^{-1}, the single row planting frequency is 72 plants per min, which is the optimal operating condition of the sweet potato seedling precision feeding and planting control system.

Conclusions

An automatic feeding method for sweet potato seedlings based on pre-treatment nursery strips is proposed. It can solve the problems of seedling leakage and labour intensity during transplanting. The seedling-feeding and planting device based on the seedling ribbon and its control system is designed. It realised automatic seedling feeding using motor-driven seedling and planting mechanisms. As a result, it avoided the problems of uneven planting spacing caused by manual seedling feeding and wheel slipping and improved the operation quality. The results of the control accuracy test of the motor speed showed that the average error of seedling-feeding motor speed is 4.04%, and the average error of planting motor speed is 3.28%. The performance test of the seedling-feeding mechanism showed that the relative errors of actual seedling-feeding spacing and clamping spacing are 7.8% and 5.1%, respectively, at medium and low operating speed levels. The planting accuracy test of seedlings showed that when the operating speed was 0.2 m•s^{-1} and 0.3 m•s^{-1}, the variation coefficients of plant spacing were 7.42% and 9.34%, respectively, controlled within 10%. The maximum theoretical planting frequency of the single ridge could reach 72 plants per min, indicating that the stability of the system was good and could meet the transplanting requirements.

The control system designed in this paper can meet the control requirements of the seedling-feeding and planting device based on the seedling belt. Furthermore, it realised the automatic and orderly seedling-feeding and control of plant spacing in the transplanting process, which is a technical prerequisite for the automatic planting of sweet potato transplanting machines. In the next step, our team will be to develop a complete set of sweet potato seedling automatic transplanting machines and field experiments.

List of abbreviations

β	Clamping angle of the flexible disc (°)
B	Seedling spacing (m)
CV_X	Coefficient of variation of plant spacing (%)
f	Planting frequency (min^{-1})
j	Number of rotations of the seedling motor
n	Number of measured plant spacing
n_1	Rotary speed of planting motor (rpm)
n_2	Rotary speed of seedling-feeding motor (rpm)
N	Number of seedlings
r	Equivalent operating radius of seedling motor (m)
r'	Real-time working radius of send seedlings motor (m)
R	Equivalent operating radius (m)
S_X	Standard deviation of spacing (cm)
V_0	Operating speed at previous moment (m•s^{-1})
V_B	Feeding line speed (m•s^{-1})
V_m	Operating speed (m•s^{-1})
w_1	Angular speed of planting motor (rad•s^{-1})
w_2	Angular speed of seedling motor (rad•s^{-1})
X	Plant spacing (cm)
$\overline{X}$	Average spacing (cm)
X_i	Measured spacing (cm)
Y	Threshold of speed difference (m•s^{-1})

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