DESIGN AND TEST ON CONTROL SYSTEM OF AUTOMATIC SEEDLING FEEDING MECHANISM FOR TRANSPLANTING MACHINE
/
移栽机自动送苗机构控制系统设计和试验

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ABSTRACT

The purpose of this study is to improve the operation reliability and running positioning accuracy of full automatic vegetable transplanting machine. To this end, in this paper, a horizontal automatic seedling-feeding (SF) mechanism for transplanting machine was designed, and the initial-position positioning control and the incremental Proportional-Integral-Derivative (PID) control algorithm based on Kalman filter (KF) were adopted to improve its operational reliability and positioning accuracy. Then, the mathematical model of the transfer function in this mechanism was analysed and MATLAB simulation was performed; the simulation results show that the KF-based incremental PID control can well suppress the influence of external disturbance to avoid system overshoot and improve the robustness and reliability of the system. Finally, the actual operation test was carried out, the test results show that at the seedling tray speed below 350mm/s, the error of moving a new seedling tray (570mm) is ≤4.19mm, and the positioning accuracy is ≥99.27%; the error of moving a column distance (42mm) is ≤1.05mm and the positioning accuracy is ≥96.79%. The automatic SF mechanism of the transplanting machine designed in this paper has a wide range of running speed and high positioning accuracy, which can meet the requirements of the positioning accuracy for the full-automatic transplanting machine feeding mechanism. This provides a reference for the design of the transplanting machine.

摘要

为了提高全自动蔬菜移栽机运行可靠性和运行定位精度，首先，设计了一种水平式移栽机自动送苗机构，并采用初始位置定位控制和融合卡尔曼滤波的增量式 PID 定位控制算法，以提高其运行可靠性和定位精度；然后，分析了该机构传递函数的数学模型，并进行 MATLAB 仿真，仿真结果表明融合了卡尔曼滤波的增量式 PID 控制能很好的抑制外界干扰的影响，可以避免系统出现超调现象，提高了系统的鲁棒性和可靠性。试验结果表明苗盘速度在 350mm/s 以下时，移动一个新苗盘(570mm)的误差≤4.19mm, 定位精度≥99.27%，移动一列距离(42mm)时误差≤1.05mm，定位精度≥96.79%。本文所设计的移栽机自动送苗机构运行速度范围大、定位精度高，可以满足全自动移栽机送苗机构定位精度的要求, 为移栽机送苗机构的设计提供了参考。

INTRODUCTION

Seedling transplanting is the main planting method in the production of protected vegetable in China. With the increase of planting quantity and labour cost, mechanical transplanting has been more applied. However, the currently used transplanting machinery is mostly the semi-automatic transplanting machine with artificial seedling feeding, which cannot fundamentally solve the problems of high labour intensity, low efficiency of transplanting and low accuracy of transplanting etc.

The field transplanting technology of plug seedlings in the developed countries is relatively mature and advanced. The Japanese full automatic transplanting machine (*Tsuga, 2000; Nambu and Tanimura, 1992*) relies on pure mechanical structures such as cam grooves etc. to realize full-automatic transplanting, but it has very complicated structure and poor adaptability to different types of plug seedlings. The Ferrari's automatic transplanting machine (*Zhou, 2009*) in Italy operates pneumatically or hydraulically, with high efficiency in the seedling picking and feeding process. In addition, the price of transplanting machines in developed countries is very high and they're developed according to the transplanting process of foreign plug seedlings, which is not applicable to domestic conditions (*Ni et al., 2015*).

At present, only a few scientific research units in China have been developing full automatic transplanting machines. The typical one is developed by *Wei et al.* (*2016*). It can realize high-speed transplanting of plug seedlings. However, the seedling-pick up mechanism remains in a high-speed operation state with excessive workload and has low reliability during long-term operation. The automatic seedling pick-up and feeding device of the plug seedling transplanting machine developed by *Han et al*. (*2013*) uses high pressure gas as the power source. It has a simple mechanical transmission system, but the vibration of the pneumatic system is large, the positioning accuracy is low and the pot seedling matrix loss is also higher. *Wu et al.* (*2013*) developed a full automatic transplanting machine with a gas-liquid damping cylinder as the driving component, but it has the disadvantages of high cost, large mechanical vibration and unstable performance. On the whole, domestic transplanter technology is relatively backward. Domestic field transplanting machines are all semi-automatic machines. Now, the development of automatic transplanting machines for field transplanting stays at the experimental research stage and there still exist the problems such as low precision and poor reliability.

In this paper, the SF mechanism of automatic transplanting machine needs to cooperate with the seedling picking mechanism for continuous start and stop, and then accurately send the seedling tray to the designated position. Too much dynamic positioning error can cause failure in the seedling picking. During operation, this SF mechanism will be affected and disturbed by such factors as seedling mass, running speed, high-frequency signal of power supply, etc., and its mechanical characteristics of the mechanism will also change after long-term operation, resulting in low long-term operational reliability and operational positioning and directly affecting the performance of the entire transplanter. In view of that above, combined with the structure of the seedling picking mechanism and feeding mechanism etc. for the full automatic transplanting machine mentioned, a horizontal automatic seedling feeding mechanism (*Han et al., 2013*) for transplanting machine was designed in this paper. Besides, the incremental PID positioning control algorithm based on Kalman filter was proposed, and the simulation analysis and prototype operation test were carried out, in order to improve the positioning accuracy and long-term reliability of the mechanism.

MATERIALS AND METHODS

Working principle and running speed of transplanting machine automatic seedling feeding mechanism

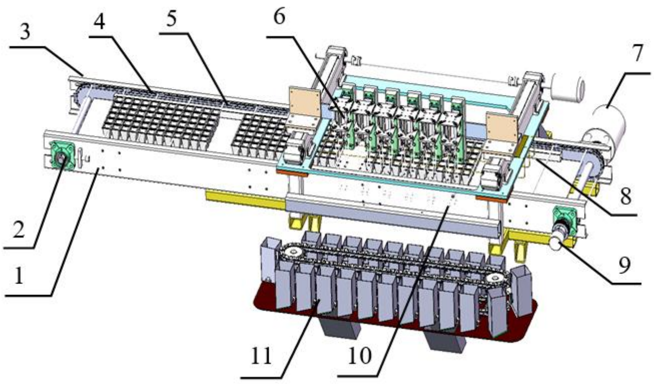

Fig. 1 - Structural diagram of automatic seedling feeding mechanism

1. Side plate 2. Tensioning wheel 3. Sprocket 4. Seedling support rod 5. Support rail 6. Seedling picking mechanism 7. Stepper motor 8. Seedling tray clamp 9. Rotary encoder 10. Position switch 11. Horizontal seedling feeding mechanism

Fig.1 shows the seedling feeding mechanism in the automatic transplanting machine. For the SF mechanism, the total length is 2,100 mm and the width is 450 mm. By the chain drive mode, the chain tension is changed by the tensioning wheel; the power source is a stepper motor which is mounted on the side plate and connected together by the coupler and the sprocket to drive the chain conveyor. The seedling support rod is installed on the chain, and three support rods support a 540 mm-wide seedling tray; the support rod is fixed with a support wheel with an outer diameter of 15mm, and the support wheel rolls on the support rail to support the chain and the load of the seedlings on the chain, thus reducing the operating resistance of the mechanism. The position of the seedling tray is settled by its position switch, i.e., Hall sensor, which is composed of a sensor probe and a circular permanent magnet. The circular permanent magnet is mounted on the support rod of the seedling conveyor belt and the sensor probe is fixed on the frame. The position is adjusted to ensure that the new seedling tray moves and stops at the set position.

During operation, three seedling trays can be placed on the SF mechanism at the same time, with the tray spacing of L_1 (30 mm). The seedling picking mechanism is used to grab the seedlings in the rightmost seedling tray, and the new seedling tray is placed on the left or the middle for the next-time picking. The design of the transplanting machine in this paper is applicable to 6 rows, 12 columns and 72 holes of seedling trays, with the spacing between the two seedlings of M (42 mm). The seedling picking mechanism has 6 seedling hands which pick seedlings per row and simultaneously work so as to improve the picking efficiency. Due to the limited spacing between adjacent seedlings, the method of picking seedlings at intervals was adopted. In operation, the seedling picking mechanism first takes the odd-numbered seedlings, and grabs the seedlings of the first to sixth rows successively. Then the seedling feeding mechanism moves a distance M (one column) from left to right shown in Fig. 2 and grabs the even-numbered seedlings. After grabbing, the conveyor belt moves the distance $L_2=W+L_1=570$ mm to bring a new seedling tray and the empty seedling tray automatically falls into the seedling tray collection box on the right. The seedling feeding mechanism automatically repeats the above working process until a stop command is issued. Each time one seedling tray is completed, the seedling tray is repositioned by its position switch to avoid the cumulative error.

The automatic SF mechanism needs to start and stop frequently during the running process. Its running speed determines whether it can deliver the seedling tray to the designated position in time at the seedling picking interval, and also directly affects the design of the positioning control algorithm. The running speed of the automatic SF mechanism is determined by the design index of the full automatic transplanting machine for the plug seedlings. The design indicators include: (1) operating speed, ranging from 0.8 to 1.5 km/h; (2) plant spacing, i.e., the distance between the two adjacent seedlings in the same row of 300-500 mm; (3) the number of rows in operations, with two rows working simultaneously.

The transplanting interval between two adjacent seedlings is calculated as:

$$t=\frac{3.6\,l}{v}\times 10^{-3} \tag{1}$$

where: l - plant spacing, mm;

v- operation speed of transplanting machine, km/h.

According to the design index of transplanting machine, at the fastest speed of 1.5 km/h and the shortest plant spacing of 300 mm, the shortest interval of transplanting between two adjacent seedlings is calculated as $t_{\min}=0.72$ s; at the longest plant spacing and the slowest speed, the longest time interval $t_{\max}=1.5$ s. The transplanting machine adopts two-row working system with six seedling hands running at the same time; each time three seedlings are transplanted in the same row, the seedling tray moves once; the move time interval is t×3 three times of the transplanting time interval between the adjacent seedlings.

The highest speed of the seedling conveyor belt appears when the new seedling tray is moved to the designated position. At this time, the longest moving distance of the seedling tray is up to $L_2=570$ mm. For the running speed of the seedling tray, according to formula (2), by taking the shortest running time interval $t_{\min}\times 3$, removing the seedling picking time of the mechanism, and plus certain time margin $t_y=0.5$ s, it's calculated as $v_{max}=343.5$ mm/s.

The sprocket bearing diameter D of belt is 96.5 mm and the maximum working speed of the stepper motor can be calculated according to formula (3) as $v_{s.max}=68$ rpm. Substituting t_{max}, it's derived as $v_{min}=142.5$ mm/s, $v_{s.min}=28.3$ rpm. Then, the running speed of the stepper motor is calculated to be 28.3-68rpm, which can meet the design requirements of the transplanter.

$$v=\frac{L}{3t-t_y} \tag{2}$$

where:

v - operation speed of seedling tray, mm/s;

L-moving distance, mm;

t - transplanting time interval, s.

t_y - time margin, s

$$v_s=\frac{v}{\pi \mathrm{D}}\cdot 60 \tag{3}$$

where: v_s - stepper motor speed, rpm;

D-sprocket bearing diameter, mm.

Positioning control algorithm

The automatic SF mechanism of the transplanting machine is a closed-loop control system composed of a stepper motor, a position switch and a rotary encoder under the control of the PLC. In order to achieve accurate positioning, an appropriate positioning control algorithm needs to be designed.

Positioning control precision analysis

The SF mechanism of the transplanting machine is driven by the stepper motor and the relationship between the running distance of the feeding mechanism and the pulse number of the stepping motor issued by the PLC is:

$$n = \frac{L}{\pi D} \cdot \frac{360 \cdot H}{\theta_0} \tag{4}$$

where:

L- running distance, mm

θ_0- standard step angle of stepping motor, 1.8°;

H- the number of subdivisions for the stepper motor driver, 16;

The maximum angle error of the stepper motor occurs when the picking is changed from the odd-numbered seedlings to even-numbered ones. The distance travelled by the stepper motor to drive the SF mechanism is L_1; according to formula (4), the number of pulses in the stepper motor is n_1=443.32 and the rounding error is Δn_1=0.32. Based on the stepper motor parameters of Table 3, the accuracy is ±5%, and the relative error of the maximum angle for the stepping motor can be calculated as α_1=0.089% by the formula (5).

$$\alpha = \frac{\Delta n_1 + 1.8 \times 5\%}{n_1} \times 100\% \tag{5}$$

The relative error of the maximum position for positioning the seedling tray is calculated by the formula (6) to be β_1=8.33% and the positioning accuracy is 1-β_1=91.67%.

$$\beta = \frac{s}{L_1} \times 100\% \tag{6}$$

where, s is the maximum position error allowed by the seedling tray positioning, which is ±3.5mm by experiment. If it exceeds this value, it will cause the failure of seedling picking, seedling damage or excessive damage of seedling substrate.

Similarly, the maximum angle relative error of the stepping motor when the seedling mechanism moves a new seedling tray to the designated position can be calculated as α_2=0.011%, the relative error of the maximum position is β_2=0.61% and the positioning accuracy is 1-β_2= 99.39%.

According to α1<β1 and α2<β2, it can be concluded that the running accuracy of the stepper motor can fully meet the seedling tray positioning requirements of the SF mechanism. However, in the actual operation process, the positioning accuracy of the seedling tray is interfered by various factors, e.g., the chain conveyor belt has nonlinear errors caused by the tooth gap, the insufficient rigidity of the drive disk component causes the stepping motor to lose the step, and the randomness of the seedling tray quality and the complexity/variability of the field operation environment disturbs the control signal. The simple positioning control is not enough to meet the system requirements and then an effective control algorithm should be taken to achieve accurate positioning control.

Kalman filter-based incremental PID Control

In order to improve the positioning accuracy, this paper designs an incremental PID position control based on Kalman filter. The block diagram of the control system is shown in Fig.2.

The trapezoidal curve, exponential curve, S-curve and PID control algorithm are often used to make position control of stepper motor. The first three algorithms can play a certain role in preventing sudden changes in speed, but with the fixed motor speed in the algorithm. After the step loss and overshoot phenomenon occurs, it must be processed by another program, which is inflexible. PID control is widely used in the field of motion control and process control, which can greatly improve the control effect. Since the stepper motor is a control object with an integral mechanism, the increments should be also controlled. Thus, in this paper the incremental PID control (*Zhao et al., 2015*) was adopted, and the incremental PID control algorithm is given as Eq. 7-10.

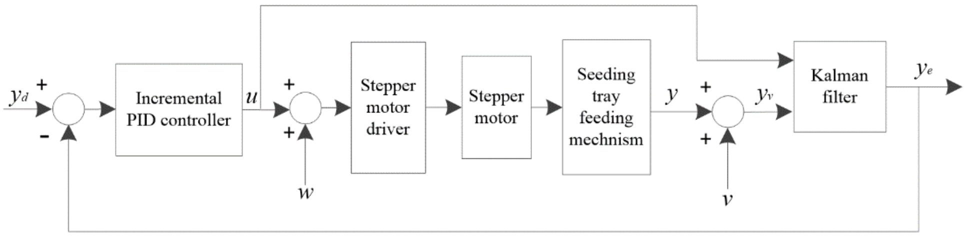

Fig. 2 - Kalman filter-based PID control system

$$u_t = u_{t-1} + \Delta u_t \tag{7}$$

$$u_{t-1} = K_p(e_{t-1} + K_i \sum_{j=0}^{t-1} e_j + K_d(e_{t-1} - e_{t-2})) \tag{8}$$

$$\Delta u_t = u_t - u_{t-1} \tag{9}$$

$$\Delta u_t = K_p(e_t - e_{t-1}) + K_i e_t + K_d(e_t - 2e_{t-1} + e_{t-2}) \tag{10}$$

where:

u_t, u_{t-1}-control amount at the time t and t-1;

e_t, e_{t-1}, e_{t-2}-position error at the time t, t-1 and t-2 ;

K_p-proportional coefficient;

K_i-integral coefficient.

From formula (7), it can be seen that the incremental PID control algorithm does not need to be accumulated and the control increment Δu_t is only related to the last two samplings, so it is influenced slightly when the malfunction occurs, so as to achieve a better control effect.

The stepper motor adopts the PTO (Pulse Train Output) pulse control mode and the PID controller output quantity u_t is the pulse frequency, at the low speed of stepper motor. In order to avoid overshoot phenomena etc., the upper limit of the u_t pulse frequency is set. According to formula (11), the pulse frequency of the stepper motor control signal corresponding to different running speeds of the seedling tray is calculated and the calculated value is rounded to obtain the upper limit of the pulse frequency (Table 1).

$$h = \frac{v}{\pi D} \frac{360 \times 16}{\theta_0} \tag{11}$$

where, θ_0 is the standard step angle of the stepper motor, 1.8°; 16 is the subdivision number of the stepper motor driver.

Table 1

Upper limit of control signal pulse frequency

Speed (mm/s)	150	200	250	300	350	400
Upper limit of the frequency (Hz)	1585	2115	2640	3170	3700	4230

Incremental PID has little calculation and also small impact range when the controller fails. However, since the transplanting machine SF mechanism is subject to a lot of interference from the outside during the operation, KF has a good effect in suppressing interference and weakening noise. For this, this paper incorporates Kalman Filtering algorithm on the basis of incremental PID control (*Kalman, 1960; Halber and Chakravarty, 2018*; *Washha et al., 2017*).

The KF uses the recursive algorithm in the time domain to perform filtering processing and estimate the state value of the current moment by using the estimated value of the previous moment and the observed value of the current moment. This algorithm can effectively suppress the control interference signals and measurement noise signals that may occur during the working process through the estimation of the system state (*Chen and Du, 2012*).

The mathematical model of control system is discretized as:

$$x_t = A x_{t-1} + B(u_t + w_t) \tag{12}$$

$$y_{v.t} = C\,x_t + v_t \tag{13}$$

where:

x_t - system state vector
$y_{v.t}$ - system measurement vector
u_t - stepper motor control
w_t - control interference signal
v - measuring interference signals
A - system state matrix
B - system control matrix
C - output observation matrix

According to the system model, the current state can be predicted based on the previous state of the system.

$$\hat{x}_{(t|t-1)} = A\,\hat{x}_{(t\text{-}1|t\text{-}1)} + B\,u_t \tag{14}$$

Where:

$\hat{x}_{(t\,|t\,-\,1)}$ - state prediction result at the time (t-1)

$\hat{x}_{(t\,-1|t\,-\,1)}$ - state optimal value at the time (t-1)

The covariance matrix $P_{(t|t-1)}$ corresponding to $\hat{x}_{(t\,|t\,-\,1)}$ is:

$$P_{(t|t-1)} = A\,P_{(t-1|t-1)}A^T + Q \tag{15}$$

Where:

$P_{(t\text{-}1|t\text{-}1)}$ - the covariance matrix corresponding to $\hat{x}_{(t-1|t\text{-}1)}$.

A_T - transpose matrix of A.

Q - system process noise covariance

Combining the measured values of the system in formula (13) with the prediction results of the current state in formula (14), the optimal estimate of the current state is derived as:

$$\hat{x}_{(t|t)} = \hat{x}_{(t|t\text{-}1)} + K_t(\,y_{v.t} - C\,\hat{x}_{(t|t\text{-}1)}\,) \tag{16}$$

where, K_t is the Kalman gain

$$K_{(t)} = \frac{P_{(t|t-1)}C^T}{CP_{(t|t-1)}C^T + R} \tag{17}$$

where: C_T - transpose matrix of C

R - measurement noise covariance matrix.

To ensure the continuous operation of KF, it is also necessary to update the covariance of the current moment:

$$P_{(t|t)} = (I - K_t C)P_{(t|t-1)} \tag{18}$$

Since the system is a single-model single measurement, then I=1 in the formula above.

The KF output is given as:

$$y_{e.t} = C\,\hat{x}_{(t|t)} \tag{19}$$

Automatic seedling feeding system simulation and seedling feeding operation test

Simulation analysis of automatic seedling feeding system

The automatic SF system is mainly composed of a stepper motor, a stepping motor driver, a driving belt and a rotary encoder. Its transfer functions are $G_d(s)$, $G_s(s)$, $G_m(s)$ and $Gr\,(s)$, respectively. The total transfer function of the system is:

$$G(s) = \frac{G_d(s)G_s(s)G_m(s)G_r(s)}{1 + G_d(s)G_s(s)G_m(s)G_r(s)} \tag{20}$$

According to the literature (*Wang et al., 2013*), the transfer function of stepper motor is given as:

$$G_d(s) = \frac{L_0 i^2 Z_r^2 / 2J}{s^2 + Ds/J + L_0 i^2 Z_r^2 / 2J} \tag{21}$$

where: L_0-inductance, [mH]; i-rated current, [A]; Z_r- number of rotor teeth; J-moment of inertia, [kg.cm^2]; D-viscous damping coefficient.

Table 2

Parameters of stepper motor

Type	Number of rotor teeth	Step angle (°)	Rated voltage (V)	Rated current (A)	Resistance (Ω)	Inductance (mH)	Static torque (N.m)	Moment of inertia (g.cm^2)	Vicious damping coefficient	Mass (kg)
HBS860H	50	1.8±5%	3.36	5.6	0.6±10%	5.5±20%	8.5	2500	0.06	4.1

According to Table 2, substituting the relevant parameters into formula (21), the stepper motor driver adopts a bridge circuit, which can be regarded as a proportional element; then, taking the subdivision selection into consideration, its transfer function is $G_d(s)$=10. The SF mechanism converts the angular displacement into the linear displacement of the seedling conveyor belt through bearing rotation, which can be regarded as a proportional element, and its transfer function is $G_m(s)=(\pi d^2)/360=0.84$. The rotary encoder can also be seen as a proportional element with a transfer function of $G_r(s)$=0.1.

$$G(s) = \frac{263.4}{s^2 + 0.04s + 577} \tag{22}$$

The system simulation program was written in M language under MATLAB. The lsqnonlin () nonlinear least squares function in MATLAB was used to optimize the PID parameters and then obtain the initial K_p, K_i and K_d. Based on this, the NCD (nonlinear control design) optimization was performed to complete the PID parameter tuning. The final setting is K_p=14.5, K_i = 1.8, K_d = 0.2.

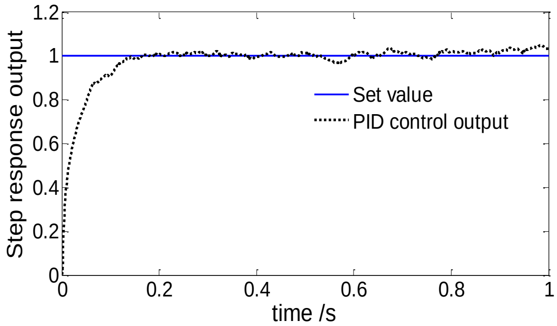

Fig. 4 - Incremental PID control response output curve

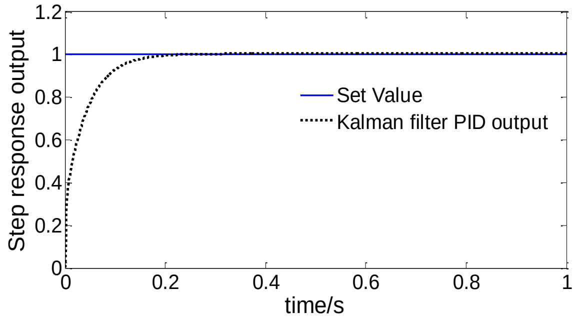

Fig. 5 - Kalman filter incremental PID control response output curve

Fig.4 and 5 show the system simulation results. The given signal by the test is a unit step signal. The blue line in the figure shows that the control interference signal and the measurement interference signal are both white noise signals with amplitude of 0.002. Fig.4 indicates that the incremental PID control is obviously affected by the external interference signal; Fig.5 indicates that the KF-based PID control effect is significantly improved, which has a good suppression of external interference, so as to avoid the overshoot phenomenon and promote the robustness and stability of the system.

Operation test of automatic seedling feeding mechanism

Test location and materials

The operation test was carried out in the Agricultural Machinery Equipment Laboratory, College of Mechanical and Electrical Engineering of Shandong Agricultural University. The 6×12 seedling tray was adopted. The transplanting machine in this paper was designed for the seedling transplanting of the eggplant, tomato, pepper, and lettuce etc. In the test, about 24-day eggplant seedlings were selected having an average seedling mass of 40 g and certain quality of the seedling substrate.

Test plan

The main purpose of this operation test is to verify the accuracy of the automatic SF mechanism under the control of the positioning algorithm *(Fan et al., 2017; Yu et al., 2018)*. By adding the seedling substrate for different seedling tray tests, the running speed and moving distance of the SF mechanism were set through the touch screen, as shown in Fig. 6.

Fig. 6 - Test control system interface of touch screen

Fig. 7 - Operation test of seedling feeding

Main test indicators:

$$\alpha = \left|1 - \frac{L_m}{L_n}\right| \times 100\% \tag{23}$$

where:

α-positioning accuracy

L_m-actual displacement, mm

L_n-theoretical displacement, mm

Test results and analysis

Fig.7 shows the feeding operation test. During the test, the SF mechanism ran smoothly under the driving of the stepping motor and the initial positioning was performed when the new seedling tray moved to the seedling position, to avoid the cumulative error and ensure accurate system positioning. Six operating speeds of 150, 200, 250, 300, 350 and 400 mm/s, and the seedling mass of 40, 50 and 60g were selected. The running speed and the average mass were combined in pairs. Each group ran 10 times and then took the average. The test results are shown in Table 3.

Table 3

Test results

Speed (mm/s)	Seedling quality (g)	Mobile new seedling tray			Moving one column (42mm)		
		Distance (mm)	Time (s)	Accuracy (%)	Distance (mm)	Time (s)	Accuracy (%)
150	40	567.83	3.961	99.62	41.83	0.478	99.59
	50	568.74	3.968	99.78	41.83	0.475	99.59
	60	569.04	3.971	99.83	42.74	0.485	98.23
200	40	568.74	3.044	99.78	41.83	0.409	99.59
	50	570.25	3.052	99.96	42.44	0.412	98.95
	60	570.86	3.054	99.74	43.05	0.415	97.5
250	40	569.95	2.480	99.98	42.14	0.369	99.67
	50	568.52	2.474	99.74	43.05	0.372	97.5
	60	571.16	2.485	99.79	42.74	0.391	98.23
300	40	568.13	2.094	99.67	42.44	0.341	98.95
	50	572.07	2.107	99.64	42.74	0.342	98.23
	60	572.98	2.110	99.48	43.35	0.345	96.79
350	40	571.46	1.832	99.74	42.44	0.321	98.95
	50	573.28	1.838	99.43	42.14	0.32	99.67
	60	574.19	1.841	99.27	42.75	0.322	98.21
400	40	572.68	1.672	99.53	42.44	0.306	98.95
	50	574.8	1.677	99.16	42.44	0.311	98.95
	60	575.71	1.689	99.01	43.66	0.322	96.05
Average value		**571.13**		**99.62**	**52.56**		**98.53**

It can be seen from Table 3 that the average positioning accuracy is 99.62% when moving a new seedling tray to the seedling position. The positioning accuracy decreases with the increase of speed and the mass of tomato seedlings. At the speed of 400mm/s, the maximum error is up to 5.7mm and the positioning accuracy is low. At the moving speed of the seedling tray of 350mm/s or less, the SF mechanism can meet the system positioning accuracy requirements.

When the seedling tray moves a distance of one column, the average value of the total positioning accuracy is 98.53%, but the maximum error is 1.6mm, meeting the positioning accuracy requirements. The main reason for the error is that with the short moving distance, the encoder can only count the integer value.

In the test process, there are also phenomena such as stepper motor overload alarm, blocking, and pulse loss etc. The running time of the stepper motor is slower than the theoretical calculation time by 0.1-0.2s, especially when the speed is greater than 350mm/s. The reason is that the torque of the stepping motor decreases as the rotation speed increases and the resistance of the feeding mechanism is greater than the torque of the stepper motor.

CONCLUSIONS

(1) In view of the high precision requirements, great load change and multiple external interference factors during the automatic seedling tray operation, the initial positioning control and the incremental PID positioning control algorithm based on Kalman filter were adopted. Based on the Siemens S7-1200 programmable controller, the electric control system of the automatic SF mechanism for the transplanting machine was designed, so as to achieve the stable operation of the seedling tray transportation.

(2) The control system model of the SF mechanism was established. The simulation experiment was carried out with MATLAB. The results show that the Kalman filter-based PID controller can effectively suppress external interference, avoid overshoot and improve the robustness and stability of the system, meeting the positioning accuracy requirements of the seedling mechanism.

(3) The eggplant seedlings in the 20-day nursery period were used for actual experiment. When the seedling speed is below 350mm/s, the error of moving a new seedling tray is ≤4.19mm and the positioning accuracy is ≥99.27%; the error for moving a column distance is ≤1.05 and the positioning accuracy is ≥96.79%, which can meet the requirements of the positioning accuracy for the feeding mechanism.

(4) In order to ensure the resistance of the SF mechanism within the torque range of the stepper motor, the maximum running speed of the mechanism is set to be 350mm/s, keeping the sprocket, etc. in good lubrication state and reducing the system resistance.

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REFERENCES

[1] Chen X.H., Du M., (2012), Multipoint temperature information fusion using sequential dual Kalman filter for temperature control system of portable RT-PCR instrument, *Journal of instrument,* vol.33, issue 2, pp.263-270;

[2] Fan G.J., Wang Y.Z., Zhang X.H., Zhao J.Y., Song Y.P., (2017), Design and experiment of automatic leveling control system for orchards lifting platform, *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, vol.33, issue 11, pp.38-46;

[3] Guo J.B., Niu H.L., Han Y.H., Dong R.J., Liu X.X., Pang C.L., (2017), Design and Experiment of Farm Ammonia Bio-oxidation Device Based on PLC, *Transactions of the Chinese Society for Agricultural Machinery,* vol.48, issue 3, pp.310-316;

[4] Halber A., Chakravarty D. (2018), Investigation of wireless tracking performance in the tunnel-like environment with particle filter, *Mathematical Modelling of Engineering Problems*, vol.5, issue 2, pp. 93-101.

[5] Han L.H., Mao H.P., Mou X.H., Hu J.P., Yang X.J., (2013), Design of Automatic Picking Up Seedling End-effector Based on Mechanical Properties of Plug Seedlings, *Transactions of the Chinese Society for Agricultural Machinery*, vol.44, issue 11, pp.260-265;

[6] Han Z.J., Yang W.Z., Zhang X.J., Guo H., Yin W.Q., (2013), Design and test of automatic feed system for tray seedlings transplanter, *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, vol.29, issue 8, pp.51-61;

[7] Kalman R.E., (1960), A new approach to linear filtering and prediction problems, *Transaction of the ASME Journal of Basic Engineering*, vol.82, issue 3, pp.35-45;

[8] Liu J.D., Cao W.B., Xu H.Z., Tian D.Y., Jiao H.B., Ouyang Y.N. (2017), Adaptive fuzzy-PID control of accurate orientation for auto-detect seedling supply device, *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, vol.33, issue 9, pp.37-44;

[9] Nambu T., Tanimura M., (1992), Development of automatic transplanter using chain pot for vegetable crops, *International Symposium on Transplant Production Systems*, issue 319, pp.541-546;

[10] Ni Y.L., Jin C.Q., Liu J., (2015), Design and experiment of system for picking up and delivering seedlings in automatic transplanter, *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, vol.31, issue 23, pp.10-19;

[11] Ryu K.H., Kim G., Ting K.C., (2001), Development of a robotic transplanter for bedding plants, *Journal of Agricultural Engineering Research*, vol.78, issue 2, pp.141-146;

[12] Tsuga K., (2000), Development of fully automatic vegetable transplanter, *Japan Agricultural Research Quarterly*, vol.34, issue 1, pp.21-28;

[13] Wang Q., Cao W.B., Zhang Z.G., Zhang P., Wang P., (2013), Location control of automatic pick-up plug seedlings mechanism based on adaptive fuzzy-PID, *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE)*, vol.29, issue 12, pp.32-39;

[14] Washha M., Mezghani M., Sèdes F. (2017), Behavioural account-based features for filtering out social spammers in large-scale twitter data collections, *Ingenierie des Systemes d'Information*, vol.22, issue 3, pp. 65-88;

[15] Wei X.H., Bao S., Liu X.K., Liu C.L., Mao H.P., (2016), Design and Experiment on Potted-seedling Automatic Transplanter Control System for Motion Coordination, *Transactions of the Chinese Society for Agricultural Machinery,* vol.47, issue 12, pp.1-7;

[16] Wu J.M., Yan H., Jin X., Guo Y., Chen K., Dong Z., (2013), Research on Disk Conveying Device and Positioning Control System for Transplanter, *Transactions of the Chinese Society for Agricultural Machinery*, vol.44, issue S1, pp.14-18;

[17] Youssef A.M., (2018), Operations of electric vehicle traction system, *Mathematical Modelling of Engineering Problems*, vol.5, issue 2, pp.51-57;

[18] Yu X.X., Zhao Y., Chen B.C., Zhou M.L., Zhang H., Zhang Z.C., (2014), Current Situation and Prospect of Transplanter, *Transactions of the Chinese Society for Agricultural Machinery*, vol.45, issue 8, pp.44-53;

[19] Zhang H., Liu F., (2018), Spatial and temporal disparities in agricultural carbon emissions in Xinjiang and decomposition of impact factors, *Chemical Engineering Transactions*, vol.66, pp.553-558;

[20] Zhao D.A., Jia W.K., Zhang Y., Zhao Y.Y., Ji W., (2015), Design of Agricultural Robot Autonomous Navigation Control Based on Improved Self-adaptive Filter, *Transactions of the Chinese Society for Agricultural Machinery*, vol.46, issue 5, pp.1-6;

[21] Zhou T., (2009), Greenhouse hole tray seedlings transplanting machine design and experimental research, *Nanjing agricultural university*.