Test bench for multi-picking detection and air-blowing removal of excess seed potatoes

Yan Liu, Guanping Wang*, Qiang Gao, Wei Sun, Sen Yang, Hongling Li

(*Mechanical and Electrical Engineering College, Gansu Agricultural University, Lanzhou 730070, China*)

Abstract: Multi-picking of spoon-chain type seed-metering devices in potato planters causes multi-seeding, which leads to yield loss and plant diseases. This study developed a dedicated test bench for multi-picking detection and air-blowing excess seed removal, which integrated a detector based on spatial capacitive sensor, an air-blowing excess seed remover, and a controller. The feasibility of multi-picking identification via maximum net capacitance change was verified through theoretical analysis and Maxwell simulation. A two-point air-blowing strategy was adopted for air-blowing excess seed removal. Taking the success rate of air-blowing excess seed removal as the evaluation index, bench tests and parameter optimization were conducted with airflow speed for air-blowing excess seed removal, potato spoon depth, and seed-metering chain speed as variable factors. The optimal parameters were determined as an airflow speed of 31.34 m/s, a potato spoon depth of 19.67 mm, and a seed-metering chain speed of 0.29 m/s. Under this optimal parameter combination, the actual success rate of air-blowing excess seed removal reached 85.5%. This test bench provides a practical technical solution for solving multi-seeding in seed potato precision seeding, and lays a solid foundation for the optimization of seeding processes and the popularization of seed potato precision seeding technology.

Keywords: seed potato, spoon-chain type seed-metering device, multi-picking detection, spatial capacitive sensor, maximum net capacitance change, air-blowing excess seed removal

DOI: 10.25165/j.ijabe.20261902.10268

Citation: Liu Y, Wang G P, Gao Q, Sun W, Yang S, Li H L. Test bench for multi-picking detection and air-blowing removal of excess seed potatoes. Int J Agric & Biol Eng, 2026; 19(2): 120–127.

1 Introduction

The combination of spoon-chain type seed-metering device and cutting seed potatoes (*Solanum tuberosum* L.) still holds a mainstream position in potato production today[1-3]. However, multi-seeding (caused by more than one seed potato in one potato spoon, which can be named multi-picking) is clearly contrary to economic logic and the basic principles of precision agriculture. It can also lead to more serious potential risks such as weak seedlings, multiple diseases, nutrient competition, yield decline, and tuber deformities. In the past decade, the monitoring and compensation of potato miss-seeding has attracted widespread attention[4,5], and some results can be industrialized[6,7]. However, there are few reports on the suppression of multi-seeding caused by multi-picking. The study on potato precision seeding in China began in 2013 and has long focused on monitoring and compensating for miss-seeding[8].

Internationally, recent technological breakthroughs have been made. For instance, one study based on an improved YOLOv5s algorithm has elevated skipped-seed detection accuracy to 98.30%, while also optimizing model lightweighting for edge computing on agricultural equipment[9]. However, another scholar designed a replanting control system using an STM32 microcontroller and laser sensors, achieving a qualified planting rate of 89.6% and reducing skipped planting to 2.46%[10]. Nevertheless, both studies are limited to "miss-seeding identification and remediation" and do not address the handling of excess seed potatoes in multi-picking scenarios, further highlighting the gap in multi-seeding suppression technologies. Currently, manual removal is the primary method for solving multi-seeding, but this approach is labor-intensive and costly. Additionally, the need to set up workstations for operators inevitably lengthens the planter by 1.2-1.5 m, reducing the flexibility of field turning[11,12], which contradicts the "high efficiency and low cost" requirements of precision agriculture. For a long time, there has been a lack of effective methods for multi-picking detection in potato seeding, and their suppression mainly relies on simple local forced vibration devices outside the seed box[13]. However, such devices have to share the same mechanical structure with miss-seeding reduction devices; moreover, Wen et al.[14] pointed out that this type of vibration device can only reduce the multi-seeding rate to 12%-15%, which fails to meet the requirements of high-quality seeding operations. Other potato seeding monitoring schemes mostly take simplicity and speed as their core objectives, which can only identify the presence or absence of seed potatoes, but are unable to determine the specific number of seed potatoes or whether multi-picking occurs. As for the deep learning-based image recognition technology mentioned earlier, although it has shown promising prospects in miss-seeding detection[15,16], it is affected by the dust generated during potato seeding operations. Due to the insufficient adaptability of cameras, its practicality in multi-picking detection remains to be verified. However, it is gratifying that some non-optoelectronic detection

Received date: 2025-10-20 **Accepted date:** 2026-03-31

Biographies: Yan Liu, Lecturer, research interest: intelligent agriculture, Email: 12006@gsau.edu.cn; **Qiang Gao**, MS candidate, research interest: agricultural machinery and intelligent equipment, Email: gsaunzds2023@163.com; **Wei Sun**, Professor, research interest: agricultural machinery and intelligent equipment, Email: sunw@gsau.edu.cn; **Sen Yang**, Associate Professor, research interest: intelligent agriculture, Email: yangsen@gsau.edu.cn; **Hongling Li**, Associate Professor, research interest: intelligent agriculture, Email: lihongling@gsau.edu.cn.

***Corresponding author: Guanping Wang**, PhD, Professor, research interest: intelligent agriculture. Mechanical and Electrical Engineering College, Gansu Agricultural University, Lanzhou 730070, China. Tel: +86-13609327629, Email: wangguanping@gsau.edu.cn.

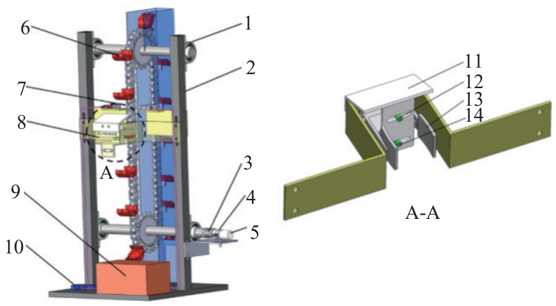
technologies are increasingly demonstrating their unique advantages[17-19]. For example, Zhou et al.[20] reliably identified faults such as interruption and blockage in wheat seeding systems based on changes in capacitance sensor signals. Inspired by this idea, Wang's team has also made forward-looking application explorations in the field of potato seeding detection. In particular, the study by Zhu et al.[21] has demonstrated the possibility of using capacitive sensing methods for multi-picking monitoring.

According to this technical route, a capacitive seed potato multi-picking detection and air-blowing excess seed removal test bench scheme is proposed first. Subsequently, the method for determining the seed potatoes multi-picking based on the maximum net capacitance change is elucidated. Next, through force analysis of the seed removal process, the minimum wind speed required to remove excess seed potatoes is determined. In the end, the main factors affecting the success rate of excess seed removal are identified, and relevant orthogonal tests are designed to obtain specific optimization parameters.

2 Overall structure and working principle

2.1 Structure of the seed discharger

The structure of the test bench for multi-picking detection and air-blowing removal of excess seed potatoes is shown in Figure 1. It primarily consists of components such as a solenoid valve, an air compressor, a spatial capacitive sensor, two Hall sensors, and a pair of pointed nozzles. The potato spoons are evenly distributed on an ear-type chain, and a 12 mm×12 mm square groove is designed on the front of each potato spoon to hold a small magnet. The bearing seat supports the shaft, ensuring stability and reducing vibration. The frame, made of Q235 material, provides structural support and stability. The coupling connects the DC motor and shaft, transmitting torque smoothly. The clamp secures the coupling, preventing loosening. The DC motor offers adjustable power output, controlling rotation speed for precise seed distribution. The potato spoon holds and lifts the potatoes, while the pointed nozzle sprays them accurately using air pressure. The 2-way 3-position solenoid valve controls airflow, enabling precise seed ejection. The sensor component supports the spatial capacitive sensor, ensuring accurate signal detection. The Hall sensors detect the magnet's position for precise control feedback.



1. Bearing seat 2. Frame 3. Coupling 4. Clamp 5. DC motor 6. Potato spoon 7. Pointed nozzle 8. Sensor sheet metal component 9. Air compressor 10. 2-way 3-position solenoid valve 11. Sheet metal 12. Hall sensor A1 13. Spatial capacitive sensor 14. Hall sensor A2.

Figure 1 Structure of the test bench for multi-picking detection and air-blowing removal of excess seed potatoes

2.2 Working principle

During operation, the 12V DC motor transmits power to the lower seed-metering chain wheel shaft via a coupling. The drive sprocket, powered by the chain wheel shaft, rotates and drives the potato spoons to move upward. The working process of the seed-metering device can be divided into four regions:

(1) Seed pickup zone

Since the primary focus of this study is to remove excess seed potatoes in case of multi-seeding, seed potatoes are manually loaded into the potato spoons in this section.

(2) Detection zone

When a potato spoon reaches Hall Sensor A1, a signal triggers the control program to begin a judgment process. The potato spoon continues upward into the detection range of the spatial capacitive sensor, where the system evaluates whether the capacitance value exceeds the preset threshold for a single seed potato. If the capacitance value exceeds the threshold, the spoon contains multi-seeding; otherwise, it contains only a single seed or none.

(3) Area for removing excess seeds

In practical seeding operations, a potato spoon may carry more than one seed away from the seed group. If the detection zone determines multi-seeding in the spoon, the spoon continues upward. When Hall Sensor A2 detects the small magnet on the potato spoon, a relay energizes the 2-way 3-position solenoid valve. The air compressor generates airflow that is directed through the solenoid valve to the pointed nozzle located behind the spoon. The nozzle blows excess seeds off the spoon, achieving automatic removal of excess seed.

(4) Seed carrying zone

After the removal of excess seed potatoes, the potato spoon, now carrying a single seed potato, moves to the driven sprocket. Under the influence of gravity, the seed potato adheres to the back of the potato spoon and slides down the seed guide chute. At the parabolic section of the lower end of the chute, the seed falls into the seedbed. This completes the entire working process and initiates the next seed pickup cycle.

3 Capacitive multiples seeding detection scheme

3.1 Principle of capacitive detection

If the dielectric between the plates of a capacitor is different, the measured capacitance value of the system will be different. Therefore, the capacitance change can be detected, providing basic information for subsequent applications[21]. The logical conversion process is illustrated in Figure 2.

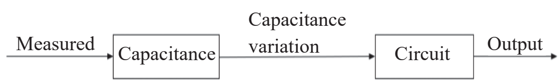


Figure 2 Principle of capacitance sensor detection for seed-metering status

The spatial capacitive sensor consists of two metal plates placed parallel to each other within an insulating medium. According to the principles of physics, when the thickness of the plates and edge effects are neglected, its capacitance C can be expressed as Equation (1)[22].

$$C=\frac{\varepsilon S}{d}=\frac{\varepsilon_0\varepsilon_r S}{d} \tag{1}$$

where, ε_0 is vacuum permittivity, F/m; ε_r is relative permittivity of the dielectric material between the plates; S is effective overlapping area of the metal plates, m²; d is distance between the two plates, m; C is capacitance, F.

From Equation (1), it can be observed that when the distance d between the plates and the effective area S remain constant, the capacitance C is directly proportional to the dielectric constant ε_r of the material between the plates. In the case of the seed potato metering device, the capacitive sensor plates not only measure air as the dielectric, but also encounter other materials, such as the potato spoon, chain, bolts, and nuts. The no-load capacitor C_0 in the non-loaded condition is as in Equation (2).

$$C_0 = \frac{\varepsilon S}{d} = \frac{\varepsilon_0 \varepsilon_{r0} S}{d} \tag{2}$$

where, ε_{r0} is the equivalent relative permittivity under no-load condition; C_0 is the no-load capacitance of the sensor, F.

The ε_{r0} can be expressed as Equation (3).

$$\varepsilon_{r0} = \varepsilon_a \frac{V_a}{V} + \varepsilon_c \frac{V_c}{V} + \varepsilon_d \frac{V_d}{V} \tag{3}$$

where, ε_a is the relative permittivity of the air at the current temperature and humidity; ε_c is the relative permittivity of the current potato spoon; ε_d is the relative permittivity of the chain; V is the volume of space between the two capacitor plates, m^3; V_a is the volume of air between the plates, m^3; V_c is the volume occupied by the potato spoon between the plates, m^3; and V_d is the volume occupied by the chain between the plates, m^3.

When a seed potato piece passes through the space between the plates while in a potato spoon, the capacitance value C_1 between plates can be expressed as:

$$C_1 = \frac{\varepsilon S}{d} = \frac{\varepsilon_0 \varepsilon_{eff} S}{d} \tag{4}$$

where, C_1 is the capacitance of the sensor with seed potato passing through, F; ε_{eff} is the equivalent dielectric constant.

The constant ε_{eff} can be expressed as Equation (5).

$$\varepsilon_{eff} = \varepsilon_a \frac{V_a}{V} + \varepsilon_b \frac{V_b}{V} + \varepsilon_c \frac{V_c}{V} + \varepsilon_d \frac{V_d}{V} \tag{5}$$

where, ε_b is the relative permittivity of the seed potato; V_b is the volume occupied by the seed potato, m^3.

The maximum net capacitance change ΔC caused by the dielectric difference between the plates is as in Equation (6).

$$\Delta C = C_1 - C_0 = \frac{\varepsilon_0 \left(\varepsilon_{eff} - \varepsilon_{r0}\right) S}{d} \tag{6}$$

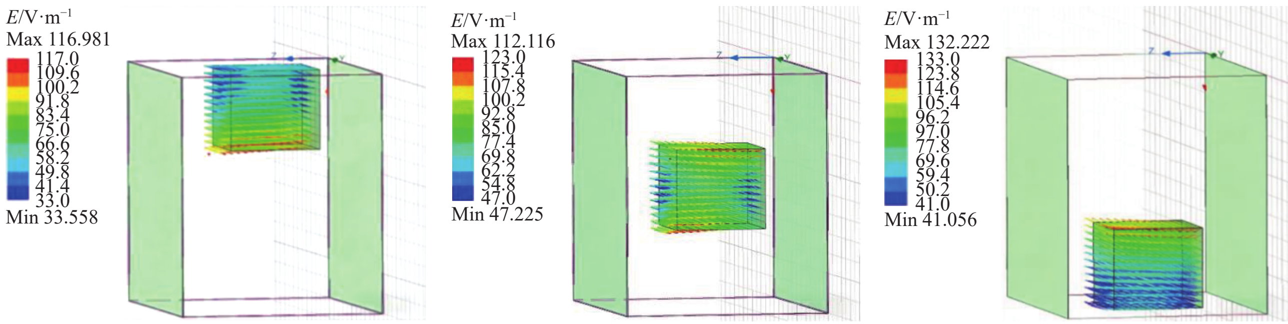
where, ΔC is the maximum net capacitance change, F.

Therefore, by real-time detection of the capacitance value and judging the maximum net capacitance change, the seed-metering status can be detected, and the occurrence of multi-picking events can be identified, thus forming the theoretical foundation for the proposed solution in this study.

3.2 Spatial capacitive sensor modeling and analysis

The seed planting chain takes seeds from top to bottom, and the potato spoon causes changes in capacitance values through the spatial capacitive sensor. According to Equation (1), if the distance between the electrodes is too large, the net capacitance fluctuation when the seed passes through the spatial capacitive sensor will be insignificant; if the distance is too small, it easily causes mechanical collisions in the system.

During the normal operation of the potato planter, the cutting process ensures that the maximum diameter of the seed potatoes is between 35-50 mm. To ensure that the seed potatoes can fully enter the spatial capacitive sensor during detection and improve the detection accuracy, the initial electrode plate height is set to 60 mm, and the width is set to 60 mm. Maxwell is used to verify the rationality of the electrode plate parameters (Ansoft Maxwell 16.0, https://www.ansys.com/). The electrode plate material is copper, with dimensions of 60 mm in length, 60 mm in width, and 0.15 mm in thickness. The area surrounding the spatial capacitive sensor is filled with air, with an air Relative Permittivity of 1.0006. A new material called "Seed potato" is created to simulate the behavior of the seed potato inside the spatial capacitive sensor. The shape is a 45 mm cube, with a Relative Permittivity of 13. The voltage applied between the capacitor plates is 12 V. The "seed potato" cube moves from top to bottom, and the electric field strength distribution at each stage is shown in Figure 3. Figures 3a-3c show the electric field strength distribution when the "seed potato" enters, reaches the center of, and leaves the spatial capacitive sensor, respectively. The relationship between the position change of the "seed potato" and the measured capacitance value is presented in Figure 4.



a. Seed potato enters the spatial capacitive sensor

b. Seed potato enters the center of the spatial capacitive sensor

c. Seed potato leaves the spatial capacitive sensor

Figure 3 Electric field distribution

From the Maxwell simulation, it is found that the capacitance variation of the capacitor plates is approximately linearly related to the movement of the "seed potato". When the "seed potato" has not entered the spatial capacitive sensor, the no-load capacitance C_0= 0.8 pF. When it moves to the center of the spatial capacitive sensor, the measured capacitance value reaches the maximum $C_{1\max}$ =1.16 pF. The simulation data indicates that during the process, the maximum net capacitance change of a single "Seed potato" through the electrodes is $\Delta C_{\max}$=$C_{1\max} - C_0$ =0.36 pF, showing a significant change in capacitance, providing the conditions for detecting the planting situation. The simulation allows for accurate determination of the capacitor plate dimensions and a general understanding of the capacitance variation range, providing necessary reference for the subsequent control system.

Based on the above simulation results, the capacitance fluctuation when a seed potato passes through the spatial capacitive sensor is in pF range. Therefore, this study uses the AD7745 chip to acquire the capacitance values. This chip features low power consumption, uses Σ-Δ conversion technology, and offers high-resolution conversion performance, with 0.02% linearity and a measurement accuracy of 1 fF, which meets the precision requirements of the spatial capacitive sensor.

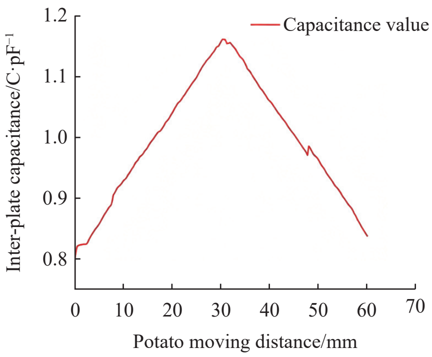


Figure 4 Graph of the relationship between seed potato position and measured capacitance value

The structure of the spatial capacitive sensor frame can be 3D printed using PLA (polylactic acid). To make the plates fit the potato spoon better, the plates are bent with a radius of 100 mm, and their shape is fine-tuned. After adjustment, the center-to-center distance between the plates remains 60 mm. A 3D model was created using SolidWorks 2022 (https://www.solidworks.com/zh-hans/support/free-downloads/), with double-sided conductive copper foil adhered to the inner side of a PLA frame. The surface protective layer is made of PTFE. The specific structure is shown in Figure 5.

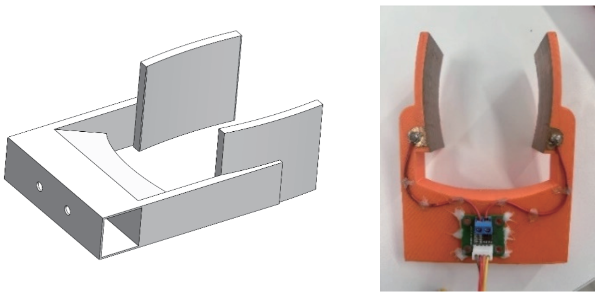


Figure 5 Structure of the spatial capacitive sensor

3.3 Principle of seed potato multi-picking detection

Since the movement of seed potatoes through the electrodes causes a change in capacitance, the planting situation of the potato spoon can be determined by setting a threshold value. The maximum net capacitance fluctuation ΔC is obtained by subtracting the empty load capacitance C_0 from each measured capacitance value C. If $\Delta C > \Delta C_{\max}$, the situation can be judged as multi-picking.

4 Excess seed removal scheme

4.1 Overview of the principle for removing excess seeds

A method of removing excess seeds using air-blow technology is adopted. Two pointed nozzles are positioned at the same height on both sides behind the seed-metering chain. The airflow removes excess seeds from the potato spoons, which then slide down a baffle and return to the seed box. The primary purpose of this study is to determine how to remove excess seed potatoes when more than one seed can be detected in a single spoon (multi-picking). For seed placement, manual seeding is used. When the spatial capacitive sensor detects multiple seeds in a potato spoon triggered by Hall sensor A1, indicating a multi-picking event, then, when Hall sensor A2 detects the small magnet on the corresponding spoon, the relay then activates the solenoid valve, and airflow is expelled through the nozzle to remove the excess seeds.

4.2 Design and parameter calculation of key components

4.2.1 Potato spoon structure

In the optimized design of the potato spoon, the internal structure should be simplified to ensure that seed potatoes experience uniform and stable forces in all orientations. Additionally, the design should allow the seeds to enter the potato spoon smoothly, improving the seed pickup efficiency. The structural parameters of the potato spoon primarily depend on the shape and size of the seed potatoes. Generally, the maximum opening diameter D and groove depth H of the potato spoon should follow the principle $D > \bar{L} > \bar{W} > 2H$, where $\bar{L}$ is the average length of the seed potatoes, and $\bar{W}$ is the average thickness[23,24].

Longshu-7, widely used in potato cultivation in Gansu Province, is used as the basis for selecting design parameters for potato spoons. With seed pieces shaped as 45 mm cubes, the opening diameter of potato spoon is designed to be 50 mm. Since the depth of seed cup directly affects the success rate of excess seed removal, an overly deep design reduces efficiency of excess seed removal, while an overly shallow design risks blowing out the seed potato at the bottom of the cup. According to the design principle, the depth of potato spoon should satisfy H<22.5 mm.

The front-end of the potato spoon is equipped with a 12 mm× 12 mm square groove to hold small magnets. The potato spoon is fabricated using 3D printing, with PLA as the material. The new potato spoon structure is shown in Figure 6. To facilitate understanding, the key technical specifications of the potato spoon are listed in Table 1.

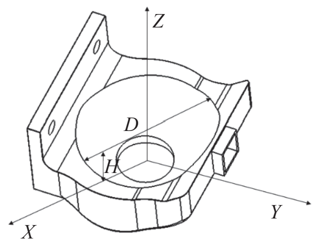


Figure 6 Optimized design of potato spoon structure

Table 1 Key parameters of potato spoon

Parameters	Specification
opening diameter (D)/mm	50
groove depth (H)/mm	19
front-end groove size/mm	12×12

4.2.2 Parameter calculation

During the process of removing excess seeds, the airflow must meet the requirements for seed removal without blowing away the seed potato at the bottom of the potato spoon. Therefore, it is necessary to establish a quantitative relationship between the airflow used to remove excess seeds and the seed weight. When the potato spoon passes through the area for removing excess seeds, the force analysis of a seed potato can be shown in Figure 7.

Taking the seed potato's center of mass as the origin, the force balance equation of the seed potato inside the seed spoon at the critical state can be described as Equation (7).

$$\begin{cases} F_c = F_f \\ F_c = F_c' \cos\beta + F_c'' \cos\alpha \\ F_f = \mu F_n \end{cases} \tag{7}$$

where, F_c' represents the forward airflow force exerted by the sharp nozzle at the left rear of the potato spoon on the seed potato, N; F_c'' represents the forward airflow force exerted by the sharp nozzle at the right, N; F_c is the resultant force from F_c' and F_c'', N; μ is the static friction coefficient between the seed potato and the potato spoon; F_f is the static friction force between the seed potato and the potato spoon, N; F_n is the support force from potato spoon, N; α and β are the included angles between the airflow direction and the forward direction of the seed potato, rad.

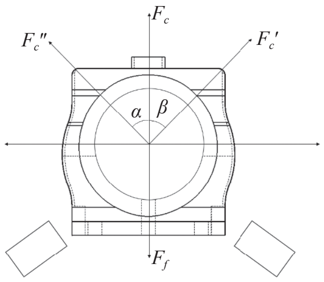


Figure 7 Force analysis of a seed potato during the seed removal process

To ensure that the excess seed potatoes are blown away from the potato spoon, the resultant forward airflow force should satisfy the following in Equation (8).

$$F_c \geq F_f \tag{8}$$

The positive pressure airflow force F_c acting on the seed potato can also be regarded as the flow resistance it experiences in the seed removal airflow field. It can be expressed as Equation (9).

$$F_c = \frac{1}{2}\rho A_p C_D v_c^2 \tag{9}$$

where, ρ represents the fluid density, kg/m^3; A_P is the cross-sectional area facing the airflow, m^2; C_D is the drag coefficient; v_c is the airflow velocity from the nozzle, m/s.

To simplify the analysis, the cross-sectional area of the seed potatoes can be considered as a sphere. Since the center of mass of the seed potato is outside the airflow field, the initial velocity can be approximated as 0. Thus, the cross-sectional area of the seed potatoes and the airflow velocity at the center of seed potato mass in the airflow field of the potato spoon can be expressed as Equation (10).

$$\begin{cases} A_p = \dfrac{\pi d_1^2}{4} \\ v_c = \dfrac{qv}{2\pi r^2(1-\cos\varphi)} \end{cases} \tag{10}$$

where, d_1 represents the seed potato diameter, m; qv is the volumetric flow rate through the nozzle, m^3/s; r is the distance from the center of seed potato mass to the center of the airflow field, m; φ is the cone angle of the airflow field, rad.

The volumetric flow rate is determined by the airflow velocity at the nozzle and the cross-sectional area, which can be expressed as Equation (11).

$$qv = \frac{\pi d^2 v_c}{4} \tag{11}$$

where, d represents the airflow tube diameter, m. By substituting Equations (10) and (11) into Equation (9), the drag force F_c experienced by a seed potato in the airflow field can be expressed as,

$$F_c = \frac{\pi\rho C_D d_1^2 d^4 v_c^2}{512 r^4(1-\cos\varphi)^2} \tag{12}$$

Based on Equation (12) and Equation (8), the required v_c can be expressed as,

$$v_c \geq \frac{16r^2(1-\cos\varphi)}{d_1 d^2}\sqrt{\frac{2\mu G}{\pi\rho C_D}} \tag{13}$$

where, G is the gravitational force on the seed potato, N.

Substituting r=0.015 m, $\varphi = 75^\circ$, d=0.03 m, d_1 =0.03 m, $\rho = 1.29\ \mathrm{kg/m^3}$, μ =0.03, G=0.27 N, and $C_D = 0.4$ into Equation (13), the condition $v_c \geq 9.8$ m/s is obtained.

5 Performance test

5.1 Test materials and equipment

Based on the principles outlined above, both hardware and software designs were made for the system, and a test bench for multi-picking detection and air-blowing removal of excess seed potatoes was manufactured as shown in Figure 8. The test seed potatoes had a moisture content of 70%-75% and a weight range of 30-50 g. The control chip used is STM32F103, with a clock frequency of 72 MHz and Flash memory capacity ranging from 16 kB to 1 MB. The digital capacitance chip used is the AD7745, with a measurement accuracy of 1 fF. An oil-free air compressor with a power rating of 3180 W and a voltage of 220 V is used. The solenoid valve is a 24 V 2-way 3-position solenoid valve. A 12 V relay is used. The drive motor used is a 12 VDC motor (SG-545126000-270K). The DC motor's speed is controlled by a motor driver module, which communicated with the host computer via USB485. Design Expert 13 software was used for experimental data analysis and parameter optimization.

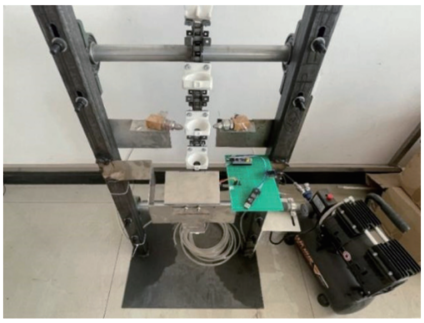


Figure 8 Test bench

5.2 Test method

The performance of the potato seed-metering and multi-picking detection device based on the spatial capacitance sensor and the maximum net capacitance change theory constructed in this research must be tested first, and then the main limiting factors affecting the success rate of excess seed removal can be investigated. Of course, due to differences in complexity, the latter is the focus of this study.

The reliability test of the potato multi-picking detection device is set up in five groups, with 50 tests per group. Among them, one seed potato is set 20 times, two seed potatoes 20 times, and three seed potatoes 10 times. The test results are listed in Table 2. Table 2 data shows that the minimum accuracy of the potato multi-picking detection device described in this study is 73.33%. Although it is not excellent, the vast majority of the samples can be identified. The main reason for misjudgment is that some seed potatoes had a particle size less than 20 mm after cutting. Two such undersized seed potatoes in one spoon were still judged as a single seed potato due to an insufficient overall capacitance change.

To determine the working parameters of the future new potato planter, performance tests were conducted on seed-metering chain speed, airflow speed for excess seed removal, and potato spoon depth. Based on the results of preliminary single-factor tests, the range for seed-metering chain speed is set to 0.2-0.6 m/s, the airflow speed for excess seed removal to 26-35 m/s, and the potato spoon depth between 18-22 mm. To obtain the optimal values for these three factors, this study uses the Box-Behnken central combination experimental design principle to conduct a three-factor, three-level response surface analysis. The success rate of excess seed removal is used as the response variable, with the test factors and levels listed in Table 3.

Table 2 Reliability test of the potato multi-picking detection device

Batch	1 seed potato	2 seed potatoes	3 seed potatoes	Multi-picking detected (times)	Multi-picking detection accuracy/%
1	20	20	10	22	73.33
2	20	20	10	25	83.33
3	20	20	10	23	76.67
4	20	20	10	22	73.33
5	20	20	10	26	86.67

Table 3 Test factors and levels

Factors	Levels		
	–1	0	1
Seed-metering chain speed	0.2	0.4	0.6
Airflow speed for excess seed removal	26	30	35
Potato spoon depth	18	20	22

5.3 Test results and analysis

5.3.1 Analysis of the impact of main restrictive factors on the success rate of excess seed removal

Factor levels are coded for the seed-metering chain speed, airflow speed for excess seed removal, and potato spoon depth of the potato seed-metering device, with the success rate of excess seed removal as the evaluation indicator. The results are listed in Table 4.

Table 4 Factor level coding and results

Serial No.	Factor			Response value
	A	*B*	*C*	*Y*
1	–1	–1	0	82.60
2	1	–1	0	80.00
3	–1	1	0	84.39
4	1	1	0	81.60
5	1	0	1	83.59
6	1	0	–1	81.59
7	–1	0	1	82.08
8	1	0	1	81.00
9	0	–1	–1	81.48
10	0	1	–1	83.20
11	0	–1	1	79.19
12	0	1	1	81.08
13	0	0	0	85.00
14	0	0	0	84.50
15	0	0	0	85.50

Note: *A*: Seed-metering chain speed, m/s; *B*: Airflow speed for excess seed removal, m/s; *C*: Potato spoon depth, mm; *Y*: Success rate of excess seed removal, %.

5.3.2 Regression equation and significance test

The Design Expert 13 data processing software is used to establish a multiple regression fit between the success rate of excess seed removal (*Y*) and the seeding speed (*A*), cleaning wind speed (*B*), and potato spoon depth (*C*). The resulting regression equation is obtained as Equation (14):

$$Y = 85 - 1.06A + 0.875B - 0.8138C - 0.0475AB + 0.23AC + 0.0425BC - 1.01A^2 - 1.84B^2 - 1.92C^2 \tag{14}$$

The regression equation is subjected to analysis of variance (ANOVA), with the results listed in Table 5. The goodness of fit of the regression model for the success rate of excess seed removal is highly significant (p<0.01), and the lack of fit of the regression model is not significant, indicating a good fit of the test data. For the regression equation of the *Y*, the p-values of the interaction terms *AB*, *AC*, and *BC* are all more than 0.05, indicating that their effects on *Y* are not significant. Meanwhile, the p-values for the other terms are all less than 0.05, indicating that they did have a significant impact on *Y*. The p-value for the lack of fit term for *Y* is 0.3785, indicating that there are no other factors influencing *Y*.

Table 5 Analysis of variance for the regression equation

Source	Sum of squares	Degrees of freedom	Mean square	*F*-value	*p*-value
Model	46.96	9	5.	14.18	0.0047**
A	8.97	1	8.97	24.37	0.0043**
B	6.12	1	6.12	16.64	0.0095**
C	5.30	1	5.30	14.39	0.0127*
AB	0.0090	1	0.0090	0.0245	0.8817
AC	0.2116	1	0.2116	0.5750	0.4825
BC	0.0072	1	0.0072	0.0196	0.8940
A^2	3.79	1	3.79	10.29	0.0238*
B^2	12.50	1	12.50	33.97	0.0021**
C^2	13.65	1	13.65	37.08	0.0017**
Residual	1.84	5	0.3680		
Lack of Fit	1.34	3	0.4467	1.79	0.3785
Pure Error	0.5000	2	0.2500		
Cor Total	48.80	14			

Note: p<0.01 (Extremely significant, **), p<0.05 (Significant, *).

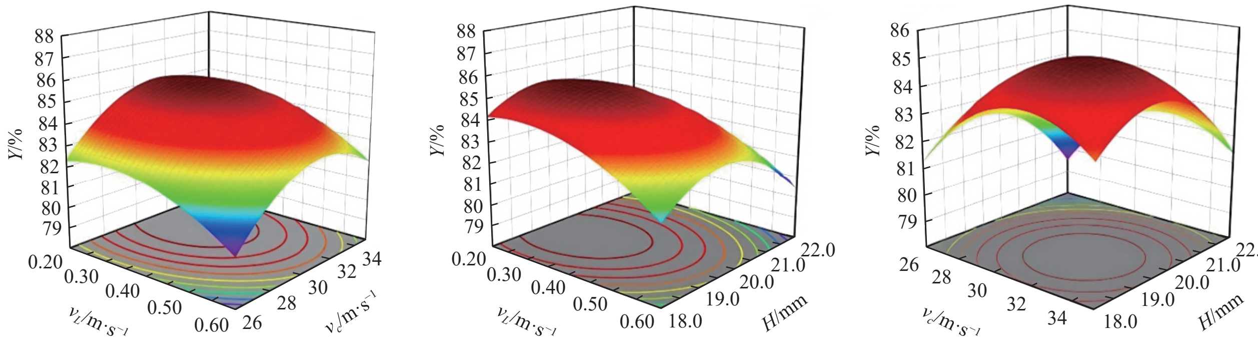
5.3.3 Response surface analysis

Based on the established regression equation model, one of the three factors is set to the 0 level, considering only the effects of the other two factors on the success rate of excess seed removal. The corresponding response surface plots are generated using Design Expert 13, as shown in Figure 9.

From Figure 9a, it can be observed that when the potato spoon depth (*H*) is at the 0 level and the seed-metering chain speed (v_L) is fixed at a certain value, the increase in airflow speed for excess seeds removal (v_c) leads to greater flow resistance acting on the seed potatoes, and the success rate of excess seed removal (*Y*) initially increases and then decreases. Similarly, at a fixed v_c, as the v_L increases, the *Y* also rises first and then falls. The *Y* is relatively high when the v_c is 30-32 m/s and the v_L is 0.30-0.55 m/s.

As shown in Figure 9b, when the v_c is at the 0 level, the response surface illustrates the effect of v_L and *H* on the *Y*. At a fixed v_L, the *Y* first increases and then decreases as the *H* increases. Likewise, at an *H*, along with the increase in v_L, the *Y* also rises first and then falls. The *Y* is relatively high when the v_L is 0.3-0.5 m/s and the *H* is 19-21 mm.

As shown in Figure 9c, when v_L is at the 0 level, the response surface illustrates the effect of v_c and *H* on the *Y*. At a fixed v_c, the *Y* initially increases and then decreases as the *H* increases. Correspondingly, at a fixed *H*, in pace with the v_c rise, the *Y* also shows a trend of first increasing and then decreasing. The *Y* is relatively high when the v_c is 28-32 m/s and the *H* is 19.0-21.5 mm.



a. H is at the 0 level b. v_c is at the 0 level c. v_L is at the 0 level

Figure 9 Effects of various factors on the success rate of excess seed removal of the seed-metering device

5.4 Parameter optimization

Based on Figure 9, which only shows the system performance under two-dimensional variables, in order to comprehensively examine the impact of v_c, v_L, and H on Y, the constraint requirements were proposed as shown in Model (15).

$$\begin{cases} \max Y \\ \text{s.t.} \begin{cases} -1 \le A \le 1 \\ -1 \le B \le 1 \\ -1 \le C \le 1 \end{cases} \end{cases} \tag{15}$$

After optimization, the optimal values of the influencing factors are determined as follows: v_L at 0.29 m/s, v_c at 31.34 m/s, and H at 19.67 mm, the model predicts the Y will be 84.78%.

5.5 Test validation

Test validation was conducted based on the optimized parameters from the model. Five repeated tests were performed under the conditions of v_L at 0.29 m/s, v_c at 31.34 m/s, and H at 19.67 mm. The optimized test results are listed in Table 6. The average success rate of excess seed removal can be 85.5%, which is very close to the optimized prediction results mentioned above.

Table 6 Optimized test results

Serial number	Success rate of excess seed removal
1	85.7
2	85.4
3	84.3
4	85.6
5	86.5
Mean value	85.5

Note: Success rate of excess seed removal is the proportion of the number of identified multi-picking potatoes that have been successfully blown away and only have one seed potato remaining.

6 Discussion

1) The working speed of the capacitance measurement system is relatively slow, taking about 5 ms, which imposes significant limitations on high-speed operations and reduces the stability of the measured capacitance data of the spatial capacitance sensor at Hall sensor A1. Therefore, adopting high-speed capacitance measurement hardware in the future is an important direction for progress.

2) Real-time acquisition of capacitance value data for spatial capacitive sensor is very important, but this value is greatly affected by surrounding structural factors, such as the length of electrode connection wires and edge effects of capacitor plate morphology. But to eliminate these additional influences through software programming, long-term data accumulation is required.

3) The accuracy of the value of C_0 is crucial in determining the maximum net capacitance change in this system. However, in fact, according to general laws of physics, there are other influencing factors for C_0, such as air humidity, temperature, etc., and these detailed factors have not yet been considered in this study.

7 Conclusions

Taking the spoon-chain type seed-metering device as the research object, a capacitive multi-picking detection and air-blowing excess seed removal test bench scheme is proposed in this study. This system mainly consisted of three parts: a spatial capacitive sensor-based potato multi-picking detection unit, an air-blowing removal excess seed potato apparatus, and a system controller.

The minimum multi-picking detection accuracy of the potato seed-metering and multi-picking detection device based on the spatial capacitance sensor and the maximum net capacitance change theory constructed in this research is 73.33%. Therefore, the vast majority of multi-picking can be identified successfully.

The seed-metering chain speed, airflow speed for excess seed removal, and potato spoon depth are considered the most influential factors to the success rate of excess seed removal. Therefore, a three-factor, three-level response surface analysis test based on the Box-Behnken central combination experimental design principle is designed. With the goal of achieving the highest success rate of excess seed removal, the analysis of interactive factors shows that the main influencing factors are in the order of airflow speed for excess seed removal, seed-metering chain speed, and potato spoon depth. The parameter optimization analysis based on Design Expert 13 shows that, under the conditions of airflow speed for excess seed removal of 31.34 m/s, seed-metering chain speed of 0.29 m/s, and potato spoon depth of 19.67 mm, the optimal success rate of excess seed removal in the system can be 84.78%.

The consistency between bench validation results and theoretical predictions fully demonstrates the reliability of the optimized parameters. These parameters can directly guide the design and development of potato planter engineering prototypes, and offer a feasible technical solution for solving the multi-seeding problem in potato precision seeding.

Acknowledgements

This research was financially supported by the Industrial Support Plan (Education Department of Gansu Province, Grant No. 2023CYZC-42), the Gansu Provincial Natural Science Foundation Special Project (Natural Science Foundation, Grant No. 26JRRA634), the National Natural Science Foundation of China

(Grant No. 32201663), and the Innovation Fund Project for College Teachers in Gansu Province (Grant No. 2025B-098).

[References]

[1] Chang X L, Teng M R, Tian Y, Zhao Z L, Han X J, Shang S Q. Current status and prospects of full mechanization in potato production. China Agricultural Machinery Equipment, 2023; 11: 6–11. (in Chinese)

[2] Pei L Q, Sun W, Wang J L, Simionescu P A. Design and experiment of a film-drilling potato seeder with eccentric coupling. Agriculture, 2024; 14(6): 933.

[3] Lv J Q, Zhang H, Li J C, Liu Z Y, Su W H, Zhu X X. Design and experiment of sorting device of potato seed cutting machine. Journal of Northeast Agricultural University, 2022; 53(11): 47–59.

[4] Sun W, Wang G P, Wu J M. Design and experiment of missing seeding detection and reseeding system for spoon-chain potato seeder. Transactions of the CSAE, 2016; 32(11): 8–15. (in Chinese)

[5] Wang G P, Sun W. Development of a missing seeding detection and compensation device for potatoes. Research of Agricultural Modernization, 2016; 37(5): 1008–1014. (in Chinese)

[6] Wang G P, Sun W, Chen L D, Zhang H, Liu X, Li H, et al. Realization of an integrated seeding and compensating potato planter based on one-way clutch. Int J Agric & Biol Eng, 2020; 13(3): 79–87.

[7] Wang G P, Sun W, Zhang H, Liu X, Li H, Yang X. Research on a kind of seeding-monitoring and compensating control system for potato planter without additional seed-metering channel. Computers and Electronics in Agriculture, 2020; 177: 105681.

[8] Liu Q W, Wu J M, Wang D, Sun W, Wang G P, Shi L R, et al. Design and research on missing seeding compensation system of 2CM-2 potato planter. Agricultural Research in the Arid Areas, 2013; 31(3): 260–266. (in Chinese)

[9] Li H, Liu X, Zhang H, Li H, Jia S, Sun W, et al. Research and experiment on miss-seeding detection of potato planter based on improved YOLOv5s. Agriculture, 2024; 14(11): 1905.

[10] Wang J, Liao M, Xia H, Chen R, Li J, Li J, et al. Study on a novel reseeding device of a precision potato planter. Agriculture, 2024; 14(10): 1824.

[11] Yang H G, Liu Z S, Ni Z W, Lin L C, Yang R B. Design and experiment of 2CM-4 potato planter. Journal of Qingdao Agricultural University (Natural Science Edition), 2017; 34(2): 137–140, 156. (in Chinese)

[12] Cai H X. Research on seeding performance improvementof potato planter in hilly areas. Master's thesis, Yangling: Northwest A&F University, 2023; 85p. (in Chinese)

[13] Liu W L, Wang H R, Wang X Y. Design and test of vibration feeding device for seed potato cutting machine. IOSR Journal of Mechanical and Civil Engineering, 2021; 21(1): 45–52.

[14] Wen B Q, Song P X, Li J B, Huang Y, Cen H L. Design and experiment of missing seeding detection and reseeding system for spoon-type potato seed-metering device. Transactions of the CSAM, 2022; 53(2): 36–46. (in Chinese).

[15] Wang J R, Liao M, Su C, Chen R, Xia H L, Li J J, et al. Study on the excess seeds removing performance of a potato precision seed metering device. Scientific Reports, 2024; 14(1): 27832.

[16] Liu W. Research on seeding rate monitoring and controlling technology based on information of seed flow rate for wheat drill. Jiangsu University, 2023. (in Chinese)

[17] Karimi H, Navid H, Mahmoudi A. Online laboratory evaluation of seeding-machine application by an acoustic technique. Spanish Journal of Agricultural Research, 2015; 13(1): 202.

[18] Zhao B, Fan X Q, Zhou L M, Li Y, Che Y, Niu K. Design and test of piezoelectric flow sensor for pneumatic seeder. Transactions of the CSAM, 2020; 51(8): 55–61. (in Chinese)

[19] Chen J G, Li Y M, Qin C J, Liu C L. Design and experiment of precision detecting system for wheat-planter seeding quantity. Transactions of the CSAM, 2019; 50(1): 66–74. (in Chinese)

[20] Zhou L M, Wang S M, Zhang X C, Yuan Y W, Zhang J N. Seed monitoring system for corn planter based on capacitance signal. Transactions of the CSAE, 2012; 28(13): 16–21. (in Chinese)

[21] Zhu L, Wang G P, Sun W, Zhang H, Liu X L, Feng B, et al. Development of a potato seed-metering status monitoring system based on a spatial capacitance sensor. Transactions of the CSAE, 2021; 37(20): 34–43. (in Chinese)

[22] Chen S Z, Jiang Z Y. General physics. Beijing: Higher Education Press. 2022; pp.205. (in Chinese)

[23] Qiao T. Design and experiment of a potato whole-tuber planter. Master's thesis. Yangling: Northwest A&F University, 2023; 77p. (in Chinese)

[24] Xia X Y. Study on intelligent measurement and control system for precision seeding of potatoes. Master's thesis. University of Science and Technology of China, 2022; 73p. (in Chinese)