Potato planter test bed based on capacitive precision seed-monitoring and miss-seeding compensation system

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Abstract: Potato seed-monitoring is the premise of its precise planting. But, for anti-dust, anti-vibration performance and durability, the existing photoelectric monitoring schemes have obvious congenital defects. So, a capacitive precision seed-monitoring idea was proposed in this study. Its theoretical basis is that the variation of dielectric between the capacitor plates will inevitably induce the fluctuation of the detected capacitance value. Therefore, the construction of a space capacitance sensor, and the acquisition of the net capacitance fluctuation caused by the seed spoon passing through the space area of the capacitor plates, were the core focuses of this study. Firstly, the system theory and working principle were introduced. Next, a space capacitance sensor that meets all the requirements was analyzed and constructed. And then, its spatial arrangement was described in detail, and most important of all, the technology roadmap of the net capacitance fluctuation measurement was put forward. For this purpose, MAX038 and GD32F407 were selected to work together to measure the capacitance. In this way, the top value of the space capacitance when a spoon passed through the space capacitance sensor was detected, at the same time, the corresponding grating encoder information was also recorded, so, the net capacitance fluctuation of this process was calculated. Based on this result, normal-seeding, miss-seeding, and multi-seeding were identified. More subtly, with the cooperation of the grating encoder, the position of the seed-metering monitoring point was configured freely. Just for miss-seeding, a predictive impact compensation concept was suggested. Based on the theories above, the software core links related to seed-monitoring and compensation control were analyzed. Finally, a potato planter test bed based on this study was built. Taking the Long-7 cutting potato as test samples, it was found that, the capacitance measurement error was no higher than 0.6%; no misjudgment on miss-seeding was found, however, for normal-seeding and multi-seeding, there was a small amount of identification of the opposite kind was found, but not more than 1.0% and 1.5%, respectively. Because of the flexibility of the seed-metering monitoring point layout, the predictive impact compensation can also be arranged according to actual needs, and the mechanism of the impact compensation system is simple and direct, which makes it cheap and fast. Nevertheless, a lower compensating seed potato tank filling rate is conducive to the average compensation success rate at an acceptable level. This research has laid the engineering foundation for the industrial application of potato non-photoelectric seed-metering monitoring and miss-seeding compensation.

Keywords: potato planter, capacitive precision seed-monitoring, space capacitance sensor, miss-seeding compensation system
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1 Introduction

The appropriate potato planting areas in China are mostly arid and semi-arid mountainous lands, which are not suitable for large-scale mechanical farming[1,2]. However, due to the pursuit of a simple structure and cost limitation, the reliability of small and medium-sized potato planters is relatively low[3-5]. Taking the combination of a spoon-chain potato seed-metering device and cutting potato seeds as an example, it is widely used because of its simplicity, and high efficiency. However, it often causes miss-seeding because of seed absence in the spoon after it has passed through the seed tank[6,7], which will inevitably lead to congenital yield reduction. At present, the typical value of this production loss scale is 5%-8%[8]. This is obviously a shocking value. Because potato has a huge planting area in the world, especially for those countries with a large population, potato must be a kind of staple food crop, and even a loss of 1% should be paid enough attention.

Manually compensation was considered to be the simplest way to solve this problem, as shown in Figure 1, however, it is not only labor intensive but also inefficient[6,8]. Furthermore, it has been proved that manual compensation can only be realized at low speed, but not at medium and high speed, in addition, the power consumption always increases by 20%-30%[9]. Therefore, the

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effective way to solve the problem is that the miss-seeding need to be identified reliably first, and then compensated quickly by an automatic device[10]. This is an important part of Precision Agriculture[11-13]. Potato planting in Europe and America is dominated by large machinery. On the one hand, the structure of large equipment is relatively mature, and its primary miss-seeding rate is comparatively low; on the other hand, in these economies, potato, as a kind of vegetable or non-staple food, has nothing to do with national food security. Therefore, this issue has not been paid attention to in these countries. However, the situation in China and India is quite different, such as the potato having officially been declared the fourth largest staple food crop in China since 2015, after rice, wheat, and maize[14]. In fact, China's research in this field just began 10 years ago, but up to now, there are still no commercial products on the market. Why is progress in this field so difficult? The core obstacles may lie in the bad planting environment (especially in arid and semi-arid areas), the limitation of sensor installation space for small and medium-sized planters, the reduction of working reliability of sensitive components due to working vibration, the difficulty of seed-monitoring caused by complex working conditions, and the contradiction between the complexity of seed potato motion control and the pursuit of the simplicity of the corresponding mechanism.

Notes: The potato planter must be equipped with a special station behind it to facilitate manual compensation for miss-seeding.

Figure 1 Manually compensation

As far as potato mechanized sowing is concerned, the precision planting ideas and achievements of many crops, especially bulk crops, can be used for reference[15,16], but there are difficult to be applied directly. For this reason, the technical idea of miss-seeding detection based on infrared photo-electricity radiating and receiving was first proposed. For example, Wang and Sun's team[17,18] put forward the decision-making scheme by Hall element electromagnet trigger. It is characterized by two-radiating and four-receiving detection, three-inspection, and two-winning judgment mechanism, which effectively solved the problems of detection moment, time-consumption, and reliability. After that, the team declared a new architecture of a two-point seed-metering state identification plan[19,20]. Which made the system response more advanced, and completely got rid of the constraints of the first-generation technology on the spatial arrangement of sensors. The accuracy of data statistics and decision-making results was not less than 99.9%. However, the system was still vulnerable to strong dust, vibration, and other external factors in the field. In addition, due to its inherent characteristics, it still could not identify the multi-seeding. So, could computer vision work? Fan et al.[21] found that image processing can be used to seed quantity statistics, miss-seeding, and multi-seeding identifications. However, image processing requires a lot of calculations, the ability of embedded computer systems was always limited, and the performance was even worse at high speeds. Most importantly, the camera was vulnerable to strong dust, external light, and other interference, so, it was difficult to be practiced in the field under complex working conditions and harsh environments. Therefore, the adoption of a non-photoelectric, fast, and simple monitoring scheme is imperative. Inspired by this guiding principle, Niu et al.[22] put forward a new idea of miss-seeding detection plan by capacitance measurement. The advantage of this idea was the monitor system is anti-dust and anti-vibration naturally, but the proposed system decision-making method still needs to carry out more extensive basic research, and its content has not been involved in multi-seeding identification.

Consequently, based on the physical fact of that, the net capacitance fluctuation caused by a seed spoon passing through the space area of the capacitor plates will be different because of the seed-metering status, first, this study proposed a more sensitive and reliable seed-metering states identification scheme. Then, a scheme of how to obtain the accurate capacitance measurement value and the net capacitance fluctuation was proposed in detail. What’s more, the criteria for miss-seeding and multi-seeding according to these detected data were given out. In the end, a kind of predictive impact compensation system was introduced, it is characterized by simplicity and rapidity, and the compensated seed potato has no position deviation.

2 Materials and methods

A space capacitance sensor can be set up by arranging the capacitor plates at a certain place on the way of the seed spoon movement. Because there is a significant difference between the permittivity of the seed tuber and the air, when a tuber passes through the detection space formed by the capacitor plates, it will inevitably cause the variation of the equivalent permittivity between the two capacitance plates, and then lead to the fluctuation of the system space capacitance value. According to this fluctuation, the seed-metering states can be judged. Therefore, the construction of the space capacitance sensor and the accurate and rapid measurement of its capacitance value is the key linkages of this study.

Although the technical scheme is not too complicated, however, on the one hand, the capacitance cannot be measured directly; on the other hand, the data usage, the hardware and software coordination, the acquisition of the miss-seeding compensation time window, the improvement of the system reliability and the effectiveness verification all need to be tested in advance. Therefore, it is necessary to carry out the test bed research in advance before the specific project development.

2.1 System theory and working principle

The process of the space capacitance value during a seed potato passing through the space of the capacitor plates can be shown in Figure 2. Neglecting the influence of edge electric field and plate thickness, the no-load capacitance of parallel plate capacitance sensor can be expressed as,

$$C_b = \frac{\varepsilon_{r1}\varepsilon_0 S}{d} \tag{1}$$

$$\varepsilon_{r1} = \varepsilon_a \frac{V_a}{V} + \varepsilon_s \frac{V_s}{V} \tag{2}$$

where, C_b is the no-load capacitance value of the space capacitance sensor, F; ε_{r1} is the relative dielectric constant of the medium between plates under no seed potato condition; ε_0 is the vacuum dielectric constant, F/m; S is the effective area of the space capacitance sensor plates, m^2; d is the distance between two plates of the space capacitance sensor plates, m; ε_a is the relative permittivity of air; ε_S is the relative permittivity of seed spoon; V is the volume surrounded by the space capacitance sensor plates, m^3; V_a is the volume of air between the space capacitance sensor plates, m^3; V_S is the volume of seed spoon between the space capacitance sensor plates, m^3.

However, in the case of a seed spoon carrying seed potato, the space capacitance value can be shown as follows:

$$C_d = \frac{\varepsilon_{r2}\varepsilon_0 S}{d} \tag{3}$$

$$\varepsilon_{r2} = \varepsilon_a \frac{V_a}{V} + \varepsilon_s \frac{V_s}{V} + \varepsilon_p \frac{V_p}{V} \tag{4}$$

where, C_d is the loaded capacitance value of the space capacitance sensor, F; ε_{r2} is the relative dielectric constant of the medium between plates when seed potato available; ε_p is the relative permittivity of seed potato; V_p is the volume of seed potato between the space capacitance sensor plates, m^3.

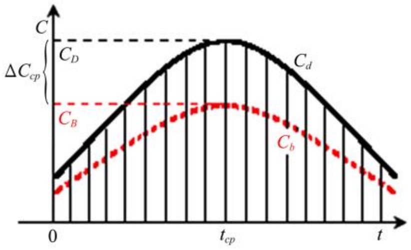


Figure 2 Description of detection principle

In the process of a seed potato passing through the space capacitor sensor, the real-time value of C_d was continuously sampled at a certain frequency, while the C_b curve was relatively fixed, and its maximum value C_B can be stored in advance. Therefore, according to Figure 2, as long as the top value C_D of C_B can be obtained, the maximum value ΔC_{cp} of the capacitance fluctuation in this process can be shown as,

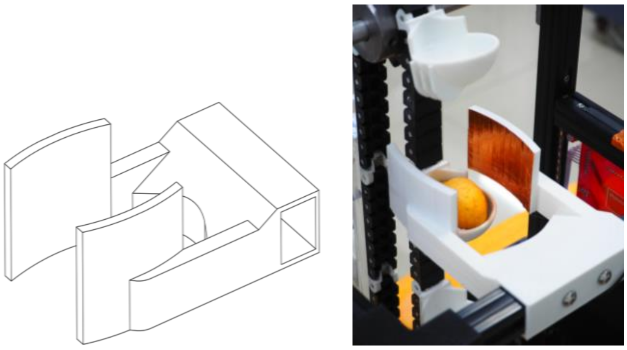
$$\Delta C_{cp} = C_D - C_B \tag{5}$$

where, ΔC_{cp} is the net capacitance fluctuation caused by a seed spoon passing through the space area of the capacitor plates, F; C_D is the maximum value of a measurement cycle of C_d, F; C_B is the maximum value of a measurement cycle of C_b, F.

Therefore, if $|\Delta C_{cp}|$ is small comparatively, it is proved that seed potato is absent on the passed seed spoon just now, which is about to produce a miss-seeding. However, if ΔC_{cp} is near a reasonable value, it is proved that seeding is normal. Furthermore, if ΔC_{cp} exceeds a higher benchmark, it is proved that there are at least two or more seed potatoes on the seed spoon, which is about to produce a multi-seeding. Since the focus of this detection scheme is the difference between the top value of real-time measured loaded space capacitance and empty spoon, therefore, not only the stability of the test data is better than that of just capacitance value directly, but also, the effect of external temperature, humidity, can be offset greatly.

2.2 Space structure of the test bed based on the new technology roadmap

According to Section 2.1, the first need was to build a space capacitance sensor. Because the diameter of a seed tuber is mostly concentrated in 30-40 mm, considering the size of the seed-metering chain and seed spoon, the basic parameters of a space capacitance sensor plates can be selected as follows: a width of 60 mm (copper plates distance), a height of 45 mm, a thickness of 0.15 mm. Acrylonitrile butadiene styrene (ABS) material was selected for the plate skeleton, which was 3D printed. In order to improve the measurement accuracy and sensitivity, the plate should be more close to the combination of the seed-metering chain and seed spoon, so, a 100 mm radius was used to bend the plates, but the average distance between the plates was still 60 mm. The specific design is shown in Figure 3. Secondly, space capacitance measurement and seed-monitoring systems should be equipped. Thirdly, based on the requirements of simplicity, rapidity, and compensated seed potato landing deviation as minimum as possible, the concept of impact compensation can be adopted, but the operation moment needs to be obtained with the information from the grating encoder. Therefore, the system space composition scheme shown in Figure 4 can be used for reference.

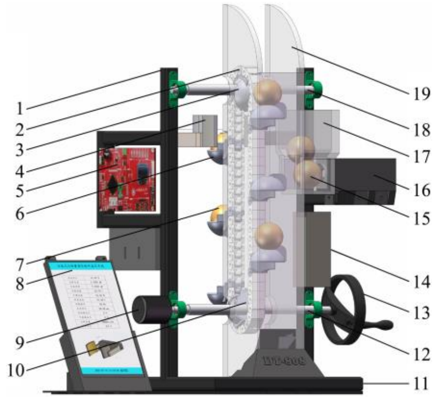


a. Structure of the space capacitance sensor

b. A potato seed is passing the space capacitance sensor

Figure 3 Space capacitance sensor and its working state diagram

How does the system work? As shown in Figure 4, First, rotate the power handle, the seed-metering chain wheel axle II, seed-metering chain wheel II, seed-metering chain wheel I, and seed-metering chain wheel axle I will rotate. Seed potatoes can be selectively placed on the seed spoons in the rising section. When a seed spoon with a seed potato passes through the space capacitance sensor, a reasonable maximum capacitance value can be measured. Similarly, if there is more than one seed potato in a spoon, a higher measured value will be obtained. Of course, if there is no seed potato in the spoon, the maximum capacitance that can be measured will be relatively small. Based on this measured space capacitance sensor data, the net capacitance fluctuation can be calculated, and not only the miss-seeding and multi-seeding can be judged, but also the specific number of them can be accurately obtained. Moreover, the position of the electromagnet installed



1. Frame 2. Seed-metering chain 3. Seed-metering chain wheel I 4. Space capacitance sensor 5. System controller 6. Seed spoon 7. Seed potato 8. LCD display 9. Grating encoder 10. Seed-metering chain wheel II 11. Base 12.Seed-metering chain wheel axle II 13. Power handle 14. Solid state relay (SSR) 15. Seed potato for compensating 16. Electromagnet 17. Compensating seed potato tank 18. Seed-metering chain wheel axle I 19. Protective groove

Figure 4 Space structure diagram of system scheme outside the protective groove can be unrestricted. When the miss-seeding decision has been made, with the auxiliary information from a grating encoder, the seed potato waiting for compensation can be struck to the missed position in the seed-metering channel. Obviously, it is a kind of no-landing deviation compensation.

2.3 Detection and control system scheme

Corresponding to the space structure diagram of the system scheme shown in Figure 4, the system detection and control scheme is suggested in Figure 5. According to the general range of the space capacitance measurement value described in relevant references[22], and the objective requirement of oscillation circuit frequency measuring through Timer/Counter (T/C) module, the processor in this project should have at least 70 million instructions per second (Mips) operation speed. Considering the scalability, GD32F407 (GigaDevice) with 106 Mips calculation capacity can be selected as CPU. The fluctuation of the equivalent permittivity of the space capacitance sensor will change the frequency of the sinusoidal oscillation circuit (with MAX038 as its core, MAXIM), and this signal will be further converted into TTL square wave (e.g., through TLV3502, TI) and sent to the T/C interface of the CPU for the space capacitance sensor value measurement. The monostable trigger receives the miss-seeding decision signal sent by the CPU, widens it, and sends it to Solid State Relay (SSR), thus, the electromagnet can be driven to realize compensation. However, the execution time of the impact compensation also depends on the signal provided by the grating encoder. The role of Wifi is to establish a local communication network in the laboratory to send data to the management computer conveniently (in practice, real-time field data can be obtained remotely by GPRS wireless), and the cloud server is used for long-term storage and data sharing. Temperature and humidity data during operation can be reordered according to the environmental information (e.g., based on SHT35) module, as a reserve for further comprehensive utilization in the future. As for the GPS signal, it is planned to be used for automatic driving during the prototype period. Other parts, such as the keyboard, data display, and CPU provide human-computer interaction channels for parameter setting, compensation channel blockage removal, and machine operation, while the reset button provides emergency shutdown, system clearing, and restart functions.

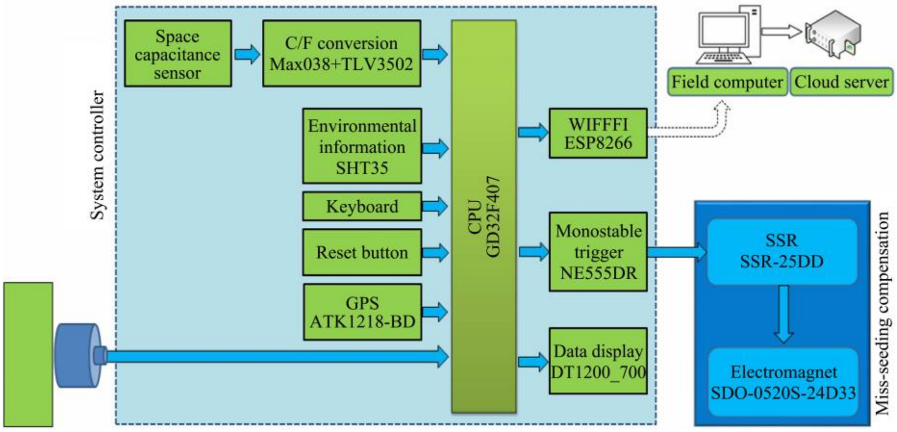


Figure 5 Detection and control system scheme

2.4 Key circuits

It is known that the capacitance value cannot be obtained directly, so, the signal frequency measurement of the sinusoidal oscillation circuit is selected here. The core of this strategy is the use of MAX038. The specific circuit configuration is shown in Figure 6a. Where, A1 (4-pin) is configured as a high level to ensure that the MAX038 produces the sinusoidal output; the space capacitance sensor to be tested (its capacitance is expressed by C_f, μF) is connected between COSC (5-pin) and GND (6-pin) of MAX038. When the seed potato passes through the capacitance sensor, C_f will undulate, so that, the frequency of the sinusoidal signal output by MAX038 will fluctuate accordingly. And then, the output sinusoidal signal will be converted to a TTL signal with TLV3502, which can be accepted by the CPU. So, the real-time frequency of the MAX038 output sinusoidal signal can be measured, and the specific C_f can be calculated too. In particular, what needs to be emphasized is that, during the movement of the seed-metering system, the net capacitance fluctuation ΔC_{cp} described in Equation (5) is just about 0.1-0.5 pF, therefore, high precision frequency measurement must be guaranteed. In addition, the sinusoidal signal frequency f_{out} (Hz) output by MAX038 is jointly controlled by the current regulating module and the external capacitor C_f between 5-6 pins. The specific constraint relationship can be shown in Equations (6) and (7).

$$I_{IN} = \frac{V_{REF}}{R_{IN}} \tag{6}$$

$$f_{out} = \frac{I_{IN}}{C_f} \tag{7}$$

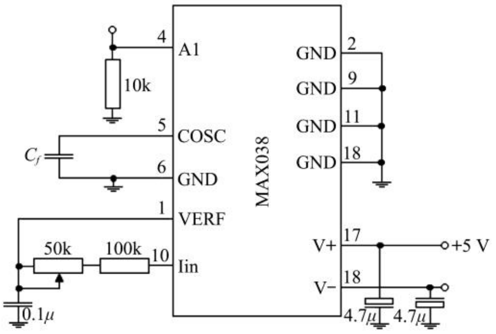
where, V_{REF} is the reference voltage output, with a value of 2.50 V; for the limited frequency fluctuation, and a better temperature coefficient, I_{IN}=20 μA is selected, so, the total resistance R_{IN} between pins 1 and 10 should be 125 kΩ. Accordingly, the curve in Figure 6) can be queried for the relationship between f_{out} and C_f.

2.5 Predictive impact compensation

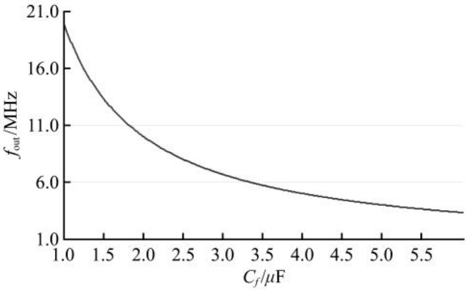
The specific impact compensation principle can be demonstrated in Figure 7. The capacitance value is sampled every 10ms, and the corresponding position of the grating encoder is recorded synchronously. Therefore, along with the seed-metering chain movement, for each seed spoon, from just entering in, until it is just away from the space enclosed by the capacitor plates, even if the seed-metering chain speed reaches 0.8 m/s (the highest speed in actual operation), at least 15 capacitance sampling values can be obtained. Meanwhile, the position signals of the grating encoder corresponding to the maximum sampling values are successively stored in the variables named position_1 until position_n (n is the number of all seed spoons). Obviously, as shown in Figure 7, the position_2 is considered to correspond to a miss-seeding, the position before it with a distance Dist2, is believed as the best position to complete the impact compensation, and this position can be calibrated as memory_2 (memory_2 corresponds to position_2, because Dist2 is fixed). Of course, the parameter Dist1, which refers to the distance between the real-time capacitance value acquisition position (Nu_gra, from grating encoder) of the space capacitance sensor and the impact compensation point, is fixed. So, the execution condition of the impact compensation can be expressed as,

$$\left|\text{Nu\_gra-memory\_2}\right| \geq \text{Dist1} \tag{8}$$

Therefore, due to the freedom of Dist1 selection, the choice of compensating position is freer than Sun et al.[17] and Wang et al.[18], which provides convenience for optimizing the spatial layout of the system.



a. Frequency measurement circuit



b. Relationship between key parameters

Figure 6 System frequency measurement scheme

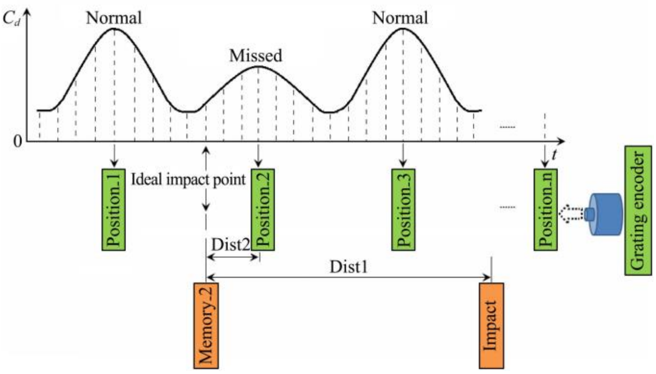


Figure 7 Principle of impact compensation execution

2.6 System software structures

The system software mainly includes the main program and Timer 1 interrupt subroutine. The flow chart structure is shown in Figure 8. The main program is responsible for parameter setting, system initialization, interrupt configuration and its enabling management, information display, human-computer interaction, C_B modification in operation, data communication, system start-up, stop control, and other operations with low real-time requirements. The interrupt subroutine of Timer 1 completes real-time space capacitance measurement, miss-seeding and multi-seeding judgment, parameter statistics, miss-seeding compensation execution, and so on. Although the software structure shown in Figure 8 is quite clear, its composition is relatively complex and huge. In order to understand the deep logic of software programming, 13 marked points in Figure 8 need to be stated clearly one by one. Therefore, four new parameters need to be defined in advance:

Natural sown number (N_1): After passing through the space capacitance sensor, the total number of seed potatoes that could be sown is normally determined by the system controller.

Miss-seeding number (N_2): The total number of seedless potato spoons judged by the system controller.

Multi-seeding number (N_3): The total number of seed spoons with more than one seed potato on one spoon is determined by the system controller.

Compensated number (N_4): The total number of the performed impact compensations.

1) The specific parameters to be set include the sampling period 1, the judgment criteria of miss-seeding and multi-seeding, and the low-speed exit tolerance. Among them, period 1 serves for Timer 1 interrupt.

2) The initial C_B acquisition is manually aided work. First, it needs to press the relevant key to start the work, and then turn the power handle to make five empty spoons pass through the space capacitance sensor continuously. Synchronously, the system stores the acquired C_b data at the sampling period 1. After the required stop key is pressed, the average of the five obtained top values is calculated as the initial data of C_B.

3) System initialization mainly includes data storage arrangement, variable preparation, CPU-related register setting, and interrupt-related function selection and priority choice.

4) Statistical data display mainly shows N_1, N_2, N_3, N_4 and relevant calculated indexes.

5) Affected by temperature, humidity, and other environmental factors, the C_B will deviate correspondingly during operation. Therefore, the average of the newly obtained two empty spoon capacitance top values can be appointed as new C_B, so as to adapt to the changing environment for more accurate ΔC_{cp} calculation.

6) Due to the objective needs of Precision Agriculture and the rapid development of the Internet of Things, focusing on the deeper use of big data in Information Agriculture in the future, using WIFI communication, this study has laid out a small wireless network. The planting coordinates, temperature, humidity, capacitance changes, and other information can be sent to the field server continuously during the operation, these data can also be backed up to the cloud platform for share. What is more important, it also provides conditions for further development of unmanned automatic planting in the future. Obviously, the server has more powerful computing performance, more channels to obtain the required information, and more powerful mission planning ability.

7) In this study, the space capacitance value C_d is updated every 10 ms, and it is obtained by calculating the frequency first and then the capacitance. The frequency f_{out} measurement is carried out by T/C-2 and T/C-3. The T/C-2 is configured as the external clock counting mode, and the T/C-3 is the internal clock timing pattern. T/C-2 is set as an interrupt priority higher than T/C-1 (Timer 1), and the overflow value is 2000. When it receives 2000 external pulses, an interrupt response will be triggered. In this interrupt function, the CPU reads the current time of T/C-3 and makes a backup. In addition, by subtracting the last backup time from the just obtained value, the time taken to generate the past 2000 external pulses can be obtained, and then the current sinusoidal signal frequency f_{out} can be calculated, and then, the immediate space capacitance value can be known through Equation (7).

8) With the information from the grating encoder, the speed v

of the seed-metering chain can be calculated. If $v \le 50$ mm/s, it can be believed that the potato planter is operating at a very low speed. In this case, the judgment of miss-seeding and multi-seeding, relevant data statistics, and their display update are suspended temporarily.

9) Because the on-chip SRAM of the selected CPU is sufficient (3072KB), and the actual number of seed spoons of potato planter is mostly 15 or less, even if v=50 mm/s, the CPU still has enough ability to store the measured capacitance values and other related data. The acquisition of C_D is based on a complete C_d rising and falling process, at the same time, its corresponding grating encoder information can be obtained simultaneously.

10) Miss-seeding is judged according to the value of ΔC_{cp}. Under normal conditions, the length, width, thickness, and weight of a cutting seed potato tuber is 30-45 mm, 30-40 mm, 20-30 mm, and 35-65 g, respectively. Therefore, ΔC_{cp} will be 0.07-0.55 pF under normal conditions, mostly 0.20-0.35 pF. Consequently, the miss-seeding judgment in this study is carried out according to the following standard:

$$\left|\Delta C_{cp}\right| \le \sigma = 0.06 \times 10^{-12}\ \text{(F)} \tag{9}$$

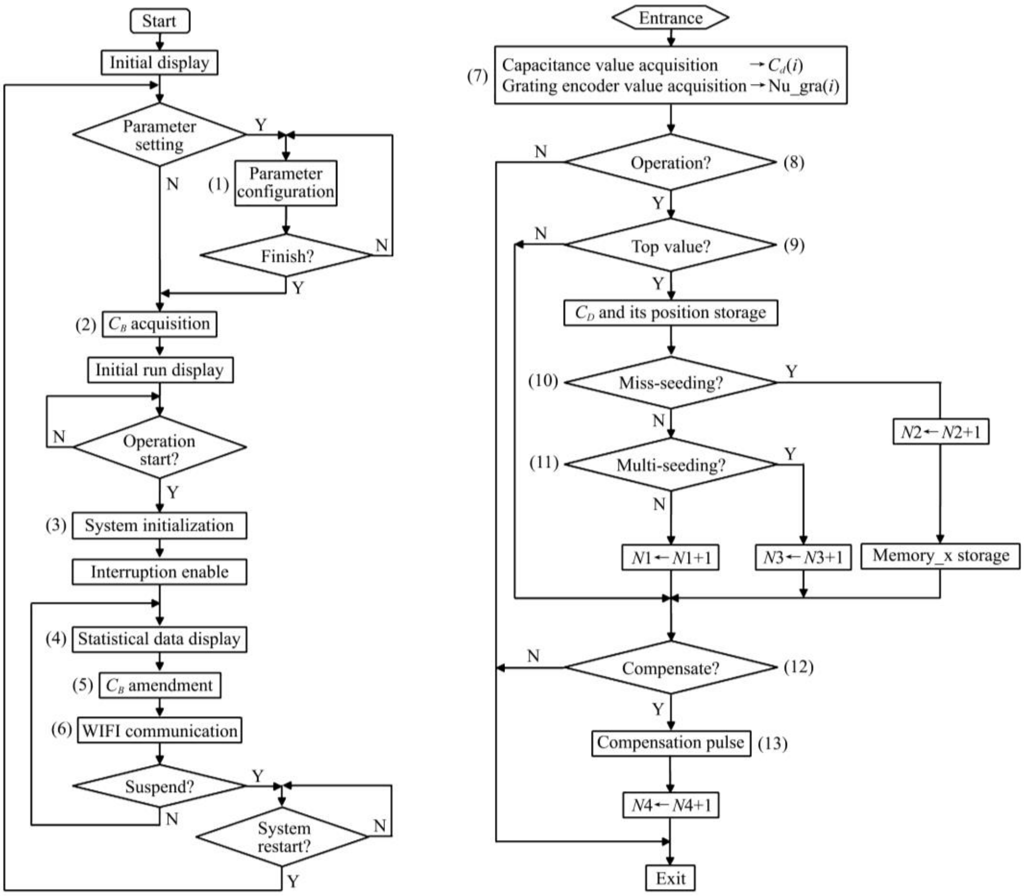
Because of the objectivity of the measurement error and the dispersion of the data itself, it is possible that C_D is slightly less than C_B in practice. However, in any case, the ΔC_{cp} under miss-seeding should be much smaller than the corresponding value under normal situations. So, it is reasonable to set a comparatively small judgment tolerance.

11) Multi-seeding judgment is the advantage of this study. Its theoretical basis is that, if there is more than one seed potato on a spoon, the ΔC_{cp} will be significantly higher than the normal level. For example, in the case of two seed tubers, the ΔC_{cp} is mostly 0.60-0.80 pF. For this reason, referring to Equation (9), the multi-seeding judgment here can be carried out according to the following rule:

$$\Delta C_{cp} \ge \delta = 0.62 \times 10^{-12}\ \text{(F)} \tag{10}$$

12) Even if it has been determined that there is a new miss-seeding, it will not be compensated immediately, and the current Timer 1 interrupt subroutine does not necessarily have the opportunity to compensate for the previous miss-seedings. Therefore, the above four paths are combined here (see Figure 8b), and the compensation execution basis is the condition shown in Equation (8).

13) In order to improve the efficiency and reduce the complexity of Timer 1 interrupt subroutine, only a start narrow pulse is given when a miss-seeding condition is met. Next, the monostable trigger circuit shown in Figure 5 wide to 50 ms meets the demand of subsequent impact compensation.



a. System main program flow chart

b. Timer 1 interrupt subroutine flow chart

Figure 8 System software structure

3 Results and analysis

At the end of July 2020, a potato planter test bed with a capacitive precision seed-monitoring and miss-seeding compensation system was manufactured in the Agricultural Engineering Training Center of Gansu Agricultural University. Its structure is exactly the same as what has been shown in Figure 4, and its detection and control system is based on Figure 5. This is a kind of principle verification test equipment for seed-monitoring of a potato planter, and the space capacitance sensor is used as new detection means. Compared with a common potato planter, it has no complete power system, and the required test power can only be provided manually by the power handle. It also has no seed box, and the test seed potatoes need to be added by hand either. Even though its overall volume is very small and easy to be moved, what needs to be emphasized is that the size of the seed-metering system has not been reduced, so that, the data obtained in this study can reflect the detection effect of the real machine as much as possible, and is conducive to cost control.

The system tests were divided into three parts. Firstly, the accuracy of the system space capacitance detection was assessed, then, the reliability of the seed-monitoring system was tested, and finally, the practice of the predictive impact compensation was examined.

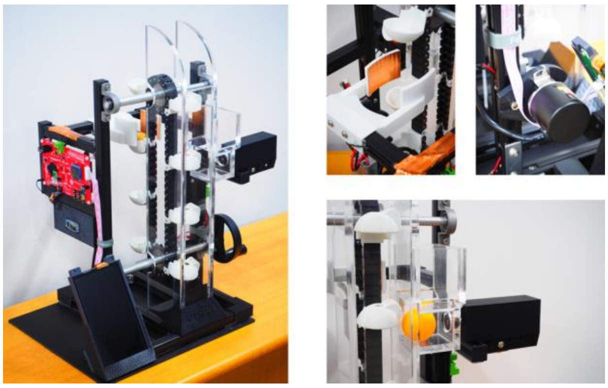


Figure 9 Potato precision seeding-metering test bed based on this study

3.1 Accuracy assessment of the space capacitance value acquisition

In order to verify the accuracy of the capacitance value obtained by the space capacitance measurement system, a comparative test was needed. 3 seed potatoes (Long-7), large, medium and small, are selected respectively. First, an empty spoon was moved to the center of the space capacitance sensor, and then the selected seed potatoes were put into it one after another for measurement. what should be noted is that, at this time, only the timing-counting method was used to measure and display the frequency, no other work was carried out, that is, only part of the software shown in Figure 8 was working. The measured data of RLC tester (AT3817D) was directly compared with the data obtained by the system, and each data was required to be measured three times. Taking the former figures as the benchmark, the relative error of the system-measured data can be calculated, and the comparison result is listed in Table 1.

Table 1 Comparative test on accuracy of space capacitance measurement

Categories	Number	Measured value/pF	Standard value/pF	Relative error/%
Empty	1	1.321	1.322	−0.1
	2	1.327	1.322	0.5
	3	1.325	1.322	0.3
Potato seed (small size)	1	1.396	1.394	0.2
	2	1.399	1.394	0.5
	3	1.392	1.394	−0.2
Potato seed (medium size)	1	1.531	1.534	−0.3
	2	1.537	1.534	0.3
	3	1.528	1.534	−0.6
Potato seed (large size)	1	1.857	1.855	0.2
	2	1.851	1.855	−0.4
	3	1.861	1.855	0.6

Note: The test temperature is 15°C and the humidity is 50% RH. For potato seed, the diameter for small, medium and large size are 20-30 mm, 30-40 mm, and 40-50 mm, respectively.

It should be noted that the temperature and humidity of the environment are the main factors affecting the measured results. That is, the data obtained are different with the changing environmental parameters. Therefore, ensuring the consistency of the measurement environment is a necessary prerequisite to being able to compare the data. Although there are huge differences between the real environment parameters in the application, it is impossible and unnecessary to do a large range of data exploration in this study. Because, on the one hand, as far as Equation (5) is concerned, ΔC_{cp} is the difference between the two measured values, and the influence of environmental factors on the two measured values is the same; on the other hand, it can be seen from Figure 8a that, C_B is also modified in real-time. Therefore, in this study, the influence of temperature and humidity can be ignored.

The data in Table 1 shows that the measured capacitance in pF, most of them can then differ after the third decimal place, which proves that the system has good data repeatability, and the relative error of measurement is no higher than 0.6%. The measured results of other randomly selected seed potatoes are similar. Therefore, the space capacitance sensor and its measurement system can meet the accuracy requirements of this study.

3.2 Reliability test of the capacitive seed-monitoring system

The function of this seed-monitoring system is, to measure the capacitance value of the space capacitance sensor accurately, so as to make decisions and carry out relevant parameter statistics. Therefore, according to the technical route of this study, it is the main embodiment of the core function to obtain the maximum value of the net capacitance fluctuation ΔC_{cp} as shown in Figure 2 and Equation (5). Then, judge the miss-seeding and multi-seeding based on Equations (9) and (10) respectively. Furthermore, make relevant quantity statistics. For this reason, three batches of tests were specially designed, including normal-seeding, miss-seeding, and multi-seeding identification. The number of seed spoons that passed through the space capacitance sensor in each batch test was 200. The specific method was: in the normal-seeding test, only one seed potato was placed on each seed spoon; for miss-seeding, all the spoons were empty, and no seed potato was placed; for multi-seeding, only two seed potatoes were given. The test results are listed in Table 2.

Table 2 Effectiveness test data of the capacitive seed-monitoring system

Test type	Total number	Actual performance			Accuracy rate/%
		Normal-seeding number	Miss-seeding number	Multi-seeding number	
Normal-seeding	200	198	0	2	99.0
Miss-seeding	200	0	200	0	100
Multi-seeding	200	3	0	197	98.5

Note: The test temperature is 15°C, the humidity is 50% RH, and v=0.2~0.8 m/s.

It can be read from the test data shown in Table 2 that, the size and shape of the seed potatoes are quite dispersive because the potato seeds here are the same as those used in the field sowing. Therefore, the actual seed-monitoring may lead to a certain degree of misjudgment. For example, in the first batch of 200 normal-seeding tests, a total of 198 normal-seeding were detected, and only 2 could be identified as multi-seeding, with a misjudgment rate of 1%. The reason was that the seed potatoes on the spoons corresponding to these 2 were large enough, so, multi-seeding was misidentified. But, this process had never been identified as miss-seeding, because the miss-seeding threshold setting is small enough, this kind of misjudgment was less likely to happen. Similarly, in the total of 200 multi-seeding tests, 197 were accurately identified, and only 3 were misjudged as normal-seeding, with a misjudgment rate of 1.5%. The reason was that every 2 seed potatoes on these 3 spoons were small enough, so they were judged as normal-seeding. However, there was no miss-seeding determination, which was obviously due to the existence of 2 seeds on the spoon, the measured space capacitance value would not be too small, and the possibility of this kind of misjudgment was also almost impossible. Among the three batches of tests, the most accurate one was the miss-seeding. In the 200 empty spoons, there was no misjudgment about normal and multi-seeding. The reason was obvious, in this batch test, all the values of ΔC_{cp} obtained according to Equation (5) were not only may positive but also may negative, however, their absolute values were small really. For all the seed potatoes within the scope of this study, Equation (9) was satisfied. Of course, if the number of tests can be increased furthermore, there will possibly be some cases to be misjudged as normal-seeding theoretically, but no case should be misjudged as multi-seeding. Therefore, the seed-monitoring scheme for a potato planter with a spoon-chain seed-metering device based on net capacitance fluctuation is feasible.

3.3 Performance examination of predictive impact compensation

After 20 no-load compensation tests, it was found that the compensation point prediction based on the principle shown in Figure 7 is accurate. However, it was obvious that the potato to be replanted must be in an additional box, that is, in a certain cavity, it can be called compensating seed potato tank. The key link of the compensating seed potato tank is the space size of the electromagnet impact room, which needs to be slightly larger than the size of a standard cutting potato. For the room, its horizontal cross-section length and width are 40 mm, and the height is 50 mm, which is conducive to the electromagnet hitting the seed potato waiting to be compensated accurately. However, due to the poor fluidity of the cutting seed potatoes, it is easy to cause blockage above the impact area, resulting in the absence of seed when the electromagnet operates. Therefore, many tests were conducted in this study. It was found that, when there were only a small amount of seeds in the compensating seed potato tank, the average compensation success rate α (%) can be almost 100%. However, if there were more and more seeds, the probability of compensation failure would increase rapidly, until finally, α will be at a relatively stable plateau of around 20%. The detailed relationship between α and the compensating seed potato tank filling rate β (%) can be shown in Figure 10.

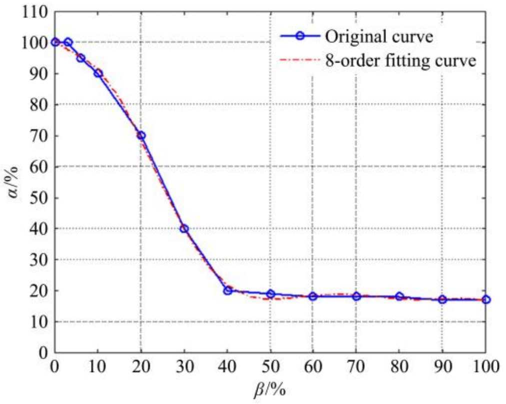


Figure 10 Relationship between the compensating seed potato tank filling rate (β) and the average compensation success rate (α)

4 Conclusions

Focused on spoon-type potato seed-metering device, in this study, a capacitive precision seed-monitoring and miss-seeding compensation system for potato planter test bed were paid close attention, and the following conclusions can be drawn:

1) A capacitive precision seed-monitoring scheme was proposed. Based on the space capacitance sensor and the continuous acquisition of real-time net capacitance fluctuation, seed-metering states are identified with high quality. Test data showed that within the range of conventional seed-metering chain operation speed, no misjudgment was found for miss-seeding judgment yet, while the misjudgment for normal-seeding and multi-seeding was 1.0% and 1.5% on opposite kinds, respectively.

2) Arrangement of monitoring and compensation actuator free from constraint. The joint use of the space capacitance sensor and grating encoder made the detection point must be carried out near the seed dropping port in the past moved to the wider upper part of the seed box now. What's more, the strong memory ability of the system controller also made the position of the compensation not have to follow the detection point closely.

3) Predictive impact compensation made the compensated seed tuber no deviation. The system controller had enough time to perform compensation, and its spatial structure is highly simplified. However, keeping the compensating seed potato tank filling rate β at a low level is a necessary condition to ensure a higher average compensation success rate α.

5 Discussion

From the concept of this study and the analysis of related test results, it was found that the potato seed-metering state detection by real-time space capacitance measured data was feasible. However, due to the limitations of some objective conditions, the following deficiencies can be shared here:

1) The main work of this study was limited to the pre-research of the miss-seeding and multi-seeding detection theory based on space capacitance measurement, and its engineering application scheme. Therefore, only the hardware and software system construction of the basic platform was paid attention to.

2) Due to the sampling frequency limitation to the space capacitance, the measured top capacitance value in each cycle may not be the real maximum figure. The solution to this problem was to reduce the interrupt cycle of T/C-1 (Timer 1), but it will put forward higher and higher requirements for CPU performance.

3) Due to the size limitation of the test bed, the detection of the compensation conditions and the performance evaluation was not considered.

4) Multi-seeding was able to identify reliably, however, the effective inhibition strategy is complex, and needs to be discussed separately.

5) Prerequisite for a successful compensation is the pre-existence of a seed potato waiting to be compensated. The test data in Section 4.3 showed that the average compensation success rate α is very sensitive to the compensating seed potato tank filling rate β, to be more precise, a smaller β is the basic premise to ensure a satisfactory α, otherwise, the blockage probability of the compensation channel will be increased sharply. Therefore, it leads to the insufficient utilization of the compensating seed potato tank, and vibration may be a feasible way to break this bottleneck.

6) Even for the same piece of land, based on the idea of this

study, the data obtained by this system will not be comparable because of the environmental difference. This is also not suitable for the storage of big data and the application of deep analysis based on it, which is required by modern precision agriculture. Therefore, the problem of data standardization in different measurement environments needs to be solved. However, it needs a lot of basic research.

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