

Article

A Plant Unit Relates to Missing Seeding Detection and Reseeding for Maize Precision Seeding

Chunling Zhang ^{1,2}, Xiaodong Xie ¹, Zihao Zheng ¹, Xiaoqing Wu ¹, Weiwei Wang ^{2,3} and Liqing Chen ^{1,2,*} 

¹ College of Engineering, Anhui Agricultural University, Hefei 230036, China

² Anhui Provincial Engineering Laboratory of Intelligent Agricultural Machinery, College of Engineering, Anhui Agricultural University, Hefei 230036, China

³ Hefei Comprehensive National Science Center, Institute of Artificial Intelligence, Hefei 230036, China

* Correspondence: lqchen@ahau.edu.cn; Tel./Fax: +86-0551-65786339

Abstract: For the current sowing machine, unavoidable reasons such as clogging of the seed row disc type opener and the seed guide tube, slipping off the ground wheel, and other unavoidable reasons lead to sowing machine leakage. This paper designs a system to detect and compensate for missed sowing of maize precision seeds. The system mainly consists of a missed seeding detection system module, a control system module, a display system module, an actuation system module, a compensation system module, etc. Detection of missed seedings uses a microcontroller as the controller and a fiber optic sensor as the detection element. Through the microcontroller's input capture and timer timing function, the total number of rows of missed and reseeded seeds is displayed on the LED display and fed back to the replenishment system to realize the alarm of missed seeds and automatic compensation. The results show that: the detection accuracy of missed seeding is more than 96%, and the highest detection accuracy can reach 100%. Less than 4% error occurred in missed seeding compensation (0.3% error in stepper motor speed, 4% error in rotation angle). The replanting rate of replanters is more than 90%; the replanting pass rate is more than 95%. When the tractor driving speed is 3~8 km/h, the sowing qualified rate is more than 90% to meet the sowing and replanting requirements.

Keywords: seed discharger; maize seeders; missed seeding detection; miss-seeding compensation



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1. Introduction

Corn is essential not only for China but also for global food crops. For large growing countries such as China and the United States, corn production accounts for 22.9% and 31.7% of total world production, respectively [1]. Corn demand is expected to reach 130 million tons by 2028 [2]. Sowing quality is one of the most critical factors affecting maize yield levels. When maize acreage is limited, increasing maize yields through technological interventions is crucial to ensure a regular supply of maize and technical measures such as maize varieties, growing conditions, and planting methods. Sowing consistency is an essential indicator of sowing qualities. A uniform distribution of seeds not only provides maximum growth space for each plant, reduces intraspecific competition, and increases yield, but also ensures that the growth of roots and seedlings remains consistent during the growth period of the plant, thus reducing output losses [3]. One of the critical factors affecting precision sowing is seeding absence. For this reason, many efforts have been made by many scholars to address the problem of missed seeding.

Leakage is a significant problem in seeding operations, mainly due to the following two aspects. On the one hand, it is due to the seeder's structure and the field environment's influence. These effects are difficult to avoid and often lead to miss-seedings [4]. A more efficient and intelligent solution is needed to address the impact of missed seeding better. Therefore, monitoring the seed discharge process and automatic compensation for missed

seeds reduces the seeder leakage rate. This is an effective means to improve the efficiency of the seeder and reduce the cost of the late manual replenishment operations and corn yield reduction. On the other hand, missed seeding would lead to reduced production. Manual labor compensation seeding is the easiest way to reduce this loss. It is thus necessary to develop a system for monitoring and automatically compensating for missed seeding—automatic sowing machine compensation for missed seeds through seed monitoring.

The seed discharge effect of the seeder directly determines the quality of the seeding operation of the planter. To monitor the sowing status of the seeder in real time, early scholars monitored the seed flow by installing sensors on the seed discharge tube below the seed dispenser to generate an electrical signal. Analyzing the signal changes generated can determine whether the seeds have missed sowing [5]. So, sensors have played a vital role throughout the history of missed-cast detection. Lowther et al. used it for missed sowing monitoring by installing a seed surface depth sensor inside the seed box, which monitors the seed layer height in real-time and gives an alarm when the seed layer height remains constant, or the seed layer is too low [6]. Mallahi et al. developed a model for monitoring the mass flow of seeds using fiber optic sensors, and the model fit was better with minor errors when the rotational speed was low and vice versa, with an overall estimated error of 5.3% [7]. Besharatia et al. designed an infrared sensor monitoring system for estimating seed flow based on Karimi et al.'s infrared (IR) sensors' design for monitoring seeds with different physical properties [8,9]. However, the aforementioned studies only involved monitoring seed flow, which could only be estimated and not accurately measured. Some scholars monitored the quality of sowing by mechanical methods. Inoti et al. added an electronic monitoring system using a monitor composed of an infrared LED lamp and a photosensitive triode to regulate the parameters of the sower by controlling a solenoid valve, using an air-suction sower as the object [10,11]. He et al. used an indirect monitoring method to estimate the seed flow by measuring the rotation angle of the slot rollers for a certain period time, but, due to the structural defects of the slot rollers, the difference in the number of seeds per rotation of the slot rollers could not be effectively monitored. This method also cannot avoid some failures, such as no seeds in the hopper and clogged seed tubes [12]. Meyer et al. monitored the neutron number using the deformation of the piezoelectric material, but the main drawback is that the seeds may collide with the piezoelectric material and be counted several times [13].

Refs. [1–13] studies are all about monitoring of seed flow and cannot accurately measure seed volume. Therefore, research on the precise monitoring of single seed sowing is becoming increasingly important. With the development of precision agriculture, computer technology, as well as Sensor Technology (ST), rapidly developed. In order to solve the problems of the above mechanical means, scholars researched more intelligent and precise technical means. Before examining these technologies, it is essential first to consider predicting the assembly size of the mechanical structure part so that the results are more convincing [14,15]. Zhang et al. designed an electronically controlled seed discharge system to address problems such as ground wheel slippage in seeders. The seeding precision is improved by measuring the rotation speed of the radar and controlling the rotation speed of the seeding system. This method can also significantly improve the seeding effect [16]. Hao et al. designed an apparatus for monitoring the seeding performance of a seeder that can effectively monitor the percentage of seed singulation, jumps, and multiples, as well as the coefficient of variation of the seed drop position [17]. Others have used capacitive, piezoelectric, ultrasonic, or image processing to monitor the amount of seed passing through the seed guide tube [18,19]. Zhang et al. designed an electro-hydraulic, hybrid-regulated garlic seeder to solve the low qualification rate and efficiency problem due to the low level of automated equipment. [20]. Xie et al. designed a monitoring system based on laser sensors and wireless serial communication. This system solves the problems of wired communication, short communication distances, and complex wiring used in traditional communication methods. Trials show that the sowing volume and success

rate are less than 1.5% [21]. Liu et al. addressed the difficulty of accurately detecting the seed flow rate when the discharged seeds are in a continuous dense state. A sensor based on seed flow reconstruction technology was designed to monitor the seed flow rate and effectively reduce the measurement error caused by seed overlap [22].

With the development of precision sowing technology, missed sowing monitoring drives the progress of the Seed Compensator System (SCS), which is also an essential means of improving sowing quality, grain yield, etc. The early technology for compensating for missed seeds mainly used motor-driven external grooved wheel seeders. In addition to the low accuracy of the used photoelectric sensor, the complex compensation structure makes it almost only theoretical [23]. On this basis, Liu et al. designed a system based on the joint work of infrared miss-seeding monitoring and a crankshaft slider compensation device, which focused on the compensation system's simplicity, rapidity, and feasibility. However, the compensation position could not be accurately located [24,25]. Precise re-seeding can be achieved by monitoring the seed leakage signal at the seed metering mouth, accelerating seed preparation, and reasonably designing the installation position of the reseeded device [26]. Based on the fact that an additional auxiliary sowing compensation device in a seeder would complicate the structure of the seeder, and the accuracy of the decompensation could not be guaranteed, Wang et al. proposed an integrated seeder with a one-way clutch for sowing compensation with a low leakage rate and accurate compensation at high seeding speeds [27].

This paper proposes a sowing interval detection method based on optical fiber sensing technology for the spoon wheel type corn planter. Based on this method, a maize precision missed sowing detection and compensation device was designed. The device enables real-time monitoring of the total amount of sown and missed seeds and reduces the rate of missed seeds with a missed seed fill function to provide a reference for designing a system to detect and compensate for missed seeding in maize precision planting.

2. Materials and Methods

2.1. Overall Structure of the Maize Planter

Figure 1 shows the whole machine for the detection and compensation of missed seeds in a maize seeder. The Beidou device (Huida Technology, Shanghai, China) equipment is installed on the tractor's roof to receive satellite signals for precise navigation. The seeder is mounted on the back of the tractor by three-point suspension and is mainly composed of fertilizer bins, a seed box, a seedbed finishing device, electronically controlled seed discharge devices, soil suppression devices, and a missed seed detection and replanting device. A hydraulic system controls the seeder lift; furthermore, the workflow of the whole unit is to start the automatic driving, and the tractor drives the planter to work to realize the integration of ditching, fertilizing, sowing, and covering the soil.

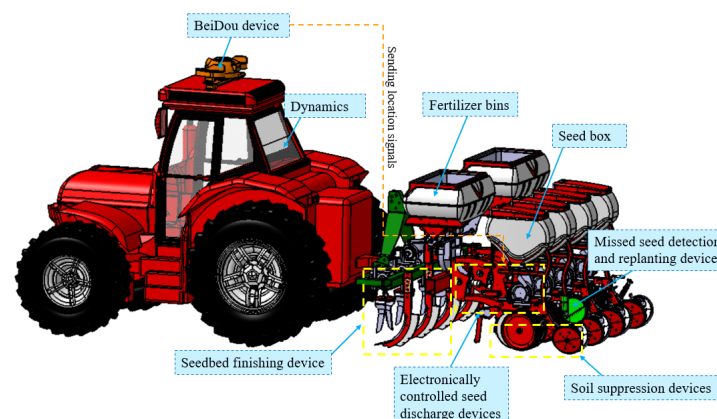


Figure 1. “Tractor, air-suction maize planter, missed seed detection and replanting” complete machine.

The schematic diagram of the proposed corn missed sowing detection and compensation system is shown in Figure 2. The system consists of the rotary encoder (CDX Technology, Shenzhen, China), air-absorbing seed discharger (Dahua Bolai, Shandong, China), fiber optic sensor (BOJKE, Shenzhen, China), replenishment stepping motor (PFDE, Shenzhen China), and replenishment seed rower (Laoliang, Hebei, China). The maize air-absorbing seed discharger mainly consists of a seedbox, seed scraper, air chamber, seed dispersal disc, seed dispersal shaft, and other parts. The installation location and device parameters are shown in Figure 2. The maize precision sowing detection and compensation system can be divided into four main parts: detection system module, control system module, display system module, and actuation system module. The detection system module consists of a fiber optic sensor and a rotary encoder for real-time monitoring of the sowing operation, collecting information such as missed sowing signals and operating speed in real time. The control module, as the system's core module, processes the signals the detection module receives and sends instructions to the execution module to make the corresponding response. The STM32F407 microcontroller (Texas Instruments, Dezhou, China) is the most critical component of the control module. The display system module is mainly used for the real-time display of seeder operating data such as seeder travel speed, theoretical grain distance, total sowing volume, missed sowing volume, and resowing volume. The actuation system module consists of a seeding absence compensation system and an alarm system. The sowing compensation system compensates for sowing leakage, and the alarm system alerts you to malfunctioning seed dispensers and blocks seed guide tubes.

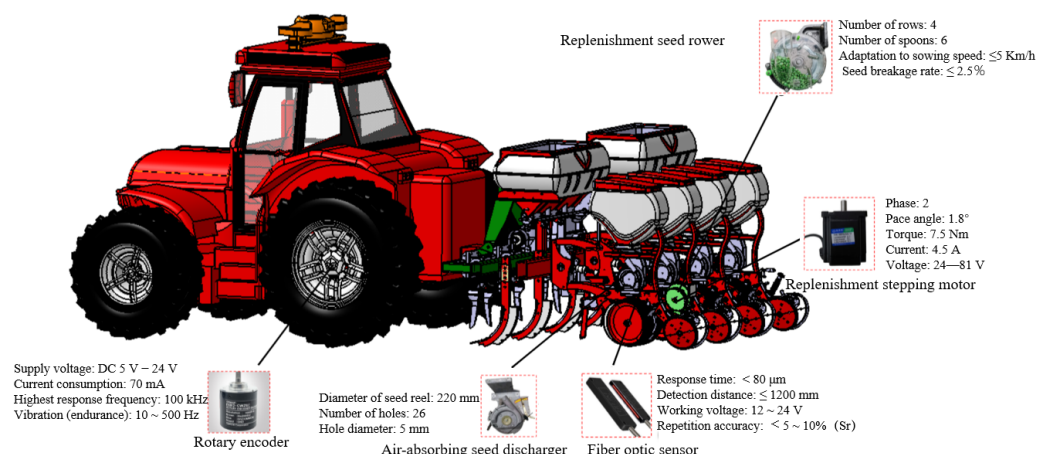


Figure 2. Structure diagram of loss sowing detection and reseeding system of precision sowing for corn.

2.2. Missed Seeding Detection System

2.2.1. Hardware Composition

The design of the leak detection device uses the Dahua 2BMYFQ series air-absorbing precision seed discharger as the research object. The maize precision sowing leak detection system consists of a power supply module, an information acquisition module, an alarm module, and a display module. The diameter of the seeding tray is 220 mm; the number of type holes is 26; the profile hole diameter is 5 mm. The sensor is a PT30QL fiber optic sensor manufactured by Shenzhen Boyi Precision Technology Co (Boyi Precision Technology, Shenzhen, China). Fiber-optic amplifier ER2-18ZW acts as a leak detection sensor for the corn precision sowing leak detection system. The fiber optic sensor mounting position is shown in Figure 3. The 86BYG250C two-phase hybrid stepper motor was selected as the power output element for the missed seeding compensation system. The motor drive model is DM860H. Table 1 shows the technical parameters of the fiber optic sensors. Different trajectories of the seeds occur during their fall due to impact with the seed guide. In this

study, a sensor is mounted on the seed guide to detect all seeds' trajectories. The installation of the fiber optic sensor is shown in Figure 3.

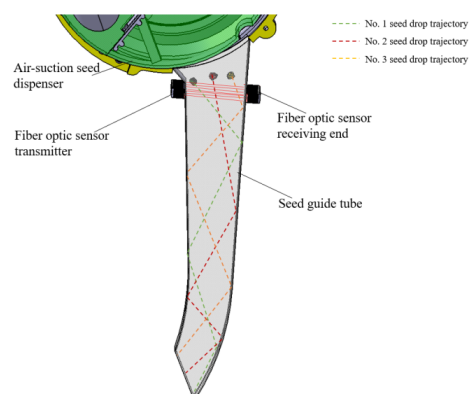


Figure 3. Fiber optic sensor installation diagram.

Table 1. Fiber optic sensor technical parameters.

Parameters	Indicators
Response time	<80 μ m
Detection distance	$\leq$ 1200 mm
Output method	NPN type normally open
Operating voltage	12~24 V
Current consumption	<30 mA
Vibration resistance	10~55 Hz, Double amplitude: 1.5 mm
Repetition accuracy	<5~10% (Sr)
Operating ambient temperature	−25~+55 °C

The STM32F407 microcontroller was chosen, and the optical fiber sensor was used as the detection element. The sensor is installed between the seed feeding port of the seed rower and the seed guide tube, and the input capture and timer timing functions of the microcontroller are used to detect the seed rowing of the seed rower. Displays of the total number of seeds discharged, missed, and reseeded are shown on the LCD (Liquid Crystal Display) screen and provides an accurate miss signal for the miss-play compensation system to be designed later. The fiber optic sensor parameters are shown in Table 1.

In this paper, we choose the Dahua Baolai 2BMYFQ series air-absorbing precision planter seed discharger as the research object. This seed rower has a seed tray diameter of 220 mm, 26, and a type hole diameter of 5 mm. The experiment was conducted at 563 Precision Seeding Laboratory, North Building, Midwest Building, Anhui Agricultural University (Precision Seeding Laboratory, Hefei, china) The test equipment is a JPS-12 type test bench (Heilongjiang Academy of Agricultural Mechanization Engineering, Heilongjiang, China) with the performance parameters shown in Table 2. The Annong 591 maize seed was selected as the corn seed. The shape of the seed is horseshoe-shaped; the 100 seed weight is 27 g; and the seed is not graded. The dimensions of 100 randomly measured seeds were averaged to be 9.94 mm long, 7.88 mm wide, and 5.24 mm thick.

Table 2. Performance Parameters of JPS-12 Test Bench.

Project	Unit	Index
Seedbed belt speed	Km/h	1.5~12
Seed discharge shaft speed	r/min	10~150
Seed spacing measurement accuracy	mm	$\pm$ 2
Pneumatic power	kPa	positive pressure: 0~35 Negative pressure: −28~5
auxiliary power	kW	7.45
Adjustment range of seed racks		Up and down: 0~400 mm Tilting: 0°~11°

The experiment selected 250 corn seeds as statistical samples, repeated the experiment for three times, and finally calculated the average value. The experiment reference is “GB/T6973-2005 single grain (precision) seeder test method”. The pass rate, reseeding rate, and omission rate were selected as evaluation indicators and calculated as follows.

$$A = \frac{n_1}{N'} \times 100\% \quad (1)$$

$$B = \frac{n_2}{N'} \times 100\% \quad (2)$$

$$C = \frac{n_0}{N'} \times 100\% \quad (3)$$

where n_1 is the number of single seeds; n_2 is the number of multiple seeds; n_0 is the number of vacancies; N' is the theoretical number of seeds in a row.

Based on the above equation, the indices can be calculated for the seeder without the MSCS (missed sowing compensation system); Table 3 shows the results of the test without the MSCS.

Table 3. Shows the test results of missing seeding compensation system not installed.

Seed Discharger	Seed Reel Speed/(r·min ^{−1})	Without Missed Seeding Compensation System		
		Passing Index/(%)	Omission Index/(%)	Replay Index/(%)
Dahua Bora	13.89	95.62	1.70	2.68
	18.51	94.89	2.68	2.43
	23.15	97.10	1.32	1.58
	27.78	94.58	2.71	2.71
	34.41	91.65	4.45	3.90
	37.04	89.53	7.86	2.61

This experiment is based on the quadratic orthogonal rotational combination design method, selecting the operating speed of 2~10 km/h, the rotation speed of the seed discharge axis of 14 r/min, 17 r/min, 24 r/min, 30 r/min, and the seed throwing height of 60~200 mm for multi-factor experiments. After processing the test data with the Design Expert software, the response surface diagram of the relationship between the operation speed, seed metering shaft speed, seed feeding height, and percent of pass is obtained, as shown in Figure 4.

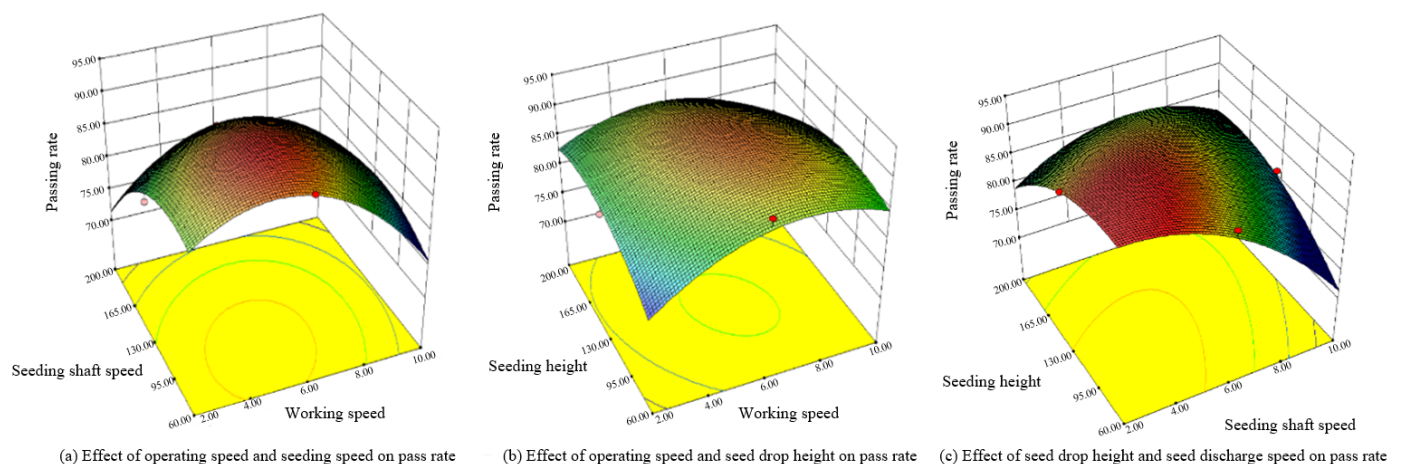


Figure 4. Surface Chart of Performance Impact of Air Suction Seed Metering Device.

2.2.2. Detection Method

Theoretical seeding intervals are calculated from the theoretical plant spacing and the travel speed of the planter before setting the seeding spacing. When the seeds are discharged from the seed meter, the optical fiber sensor installed between the seed meter dripper and the seed guide tube will cause a change in the grating. At this point, the microcontroller will obtain a low-level signal, and the sensor will output a high level in the normal state. Thus, the seeds are continuously discharged from the seed row through the fiber optic sensor, and the microcontroller gets a uniformly varying pulse sequence. The time interval between the two low levels is the actual time between the two seeds falling. The microcontroller measures the duration of this time and then compares it with the standard seeding interval to determine whether the seeder has missed sowing. In the event of a missed sowing, the microcontroller calculates the speed of the seed filler by using the equation of the relationship between the working speed of the seed filler and the speed of the seed reel. The seeding signal is then sent down to the stepper motor driver as an electrical pulse, which drives the stepper motor to execute the seeding command.

Set the sowing spacing before the planter starts work. Once in the field and starting operations, wheel-mounted speed encoders read the travel speed of the planter in real-time. The theoretical seeding interval is calculated from the theoretical plant spacing and seeder travel speed. The seed dispenser starts rotating, and the discharge of seeds from the seed dispenser through the fiber optic sensor mounted between the seed dispenser drop and the seed guide tube causes a change in the grating. At this point, the microcontroller will obtain a low-level signal, and the sensor will output a high level in the normal state. This way, the seeds are continuously discharged from the seed row through the fiber optic sensor. The microcontroller obtains a uniformly varying pulse sequence. The time interval between two low levels is the actual time interval between the two seeds falling. The pulse sequence is shown in Figure 5.

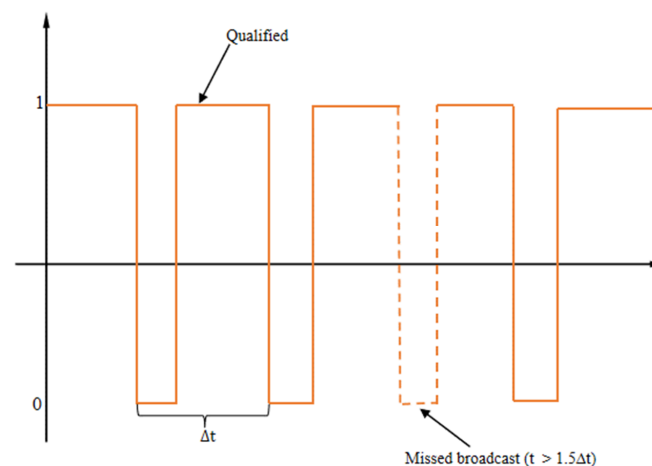


Figure 5. Pulse sequence diagram.

The seed flow formed by the seeds exiting the seed releaser and falling can be seen as a mass flow. It is characterized by the three conditions of Poisson flow: First of all, there is smoothness. For a sufficiently small period, it is only related to the length of the time interval and not to the starting point of the time. Secondly, there are no after-effects, being independent of each other and not related to the previous situation. In addition, finally, there is commonality, meaning a negligible probability of 2 or more events occurring in a sufficiently small-time interval.

From the above, it can be shown that the seed drop per unit time obeys the Poisson distribution:

$$P_n = \frac{(\lambda t)^n}{n!} \cdot e^{-\lambda t}, n = 1, 2, \quad (4)$$

Then, the time interval between the fall of the 2 seeds follows an exponential distribution:

$$f(t) = \lambda e^{-\lambda t}, t > 0 \quad (5)$$

Let the actual grain spacing of the row of seeds be l . Then, according to the national standard [5], when the actual grain spacing is less than 0.5 times the X_r , theoretical grain spacing by $l < 0.5X_r$, it can be judged as reseeding. When the actual grain spacing is greater than or equal to 0.5 times the theoretical grain spacing and less than or equal to 1.5 times the theoretical grain spacing, both $0.5X_r \leq l \leq 1.5X_r$, the sowing can be judged as normal.

The theoretical seeding grain spacing can be converted into the theoretical seeding time interval and compared with the actual seeding time interval, thus determining the seeding status. From the theoretical grain distance X_r and the forward speed v of the seeder, we can find the theoretical row time interval Δt . Criteria for determining sowing status by actual seeding interval t according to national standards are:

$$t \begin{cases} \in [0.5\Delta t, 1.5\Delta t] \text{ (Qualified)} \\ > 1.5\Delta t \text{ (Missed broadcast)} \\ < 0.5\Delta t \text{ (Repeat seeding)} \end{cases} \quad (6)$$

2.3. Reseeding System

2.3.1. Design of Reseeding Device

The compensation unit consists of a seed filler, a stepper motor, and a stepper motor driver. This design uses the old Liang six scoop wheel type maize seeder as a replanting seeder. The 86BYG250C two-phase hybrid stepper motor was selected as the power output element for the missed seeding compensation system. The motor driver was selected from the DM860H model. The output shaft of the stepper motor is connected to the rotating shaft of the seed rower, and the output line is connected to the signal end of the driver. The installation diagram is shown in Figure 6. The STM32 microcontroller will send a seeding instruction to the driver when it receives the seeding absence signal as an electrical pulse signal. The driver drives the stepper motor to rotate the seed filler for seed filling.

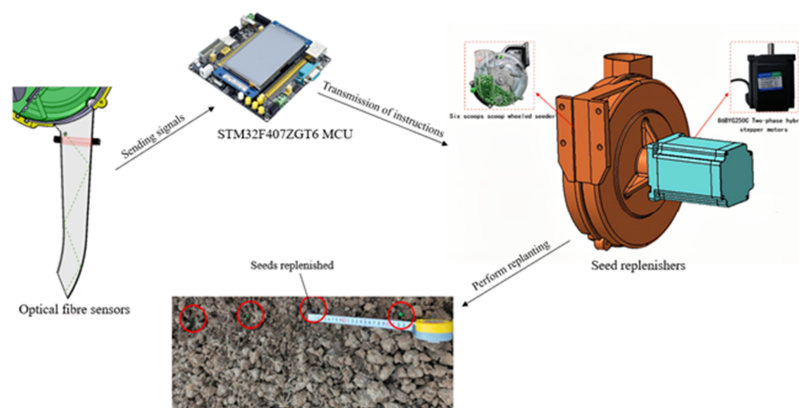


Figure 6. Diagram of the replay system start-up process.

2.3.2. Parameters Analysis of Reseeding System

Design of a self-compensating system for missed seeding based on stepper motors with a view to accurate replanting. There are two main types of replanting:

- (1) Self-compensation for seeding absence s : Seed replenishment occurs by controlling the rotation of the seeding motor when the seeder is missed. The missed seeding detection sensor detects a seeding absence signal and sends it to the controller. The controller sends a replenishment command to the motor drive to accelerate the seed rower for replenishment. Because the seed rower is self-replenishing, it considers the

response time of the sensor and controller. Therefore, the detection of missed sowing is usually performed before the seeds are discharged from the seeding apparatus.

- (2) Missed seeding additional compensation: Add a set of seed dispersers to the original seed metering device for replanting. Based on the original seed rows, a set of seed rows is added to replenish seeds, and the replenishment seed row is usually installed behind the original seed row and driven by the motor. When the missed seeding detection device detects the occurrence of missed seeding, the controller issues a replanting command. The seeding drive motor quickly responds by turning a certain angle to complete the seeding work. An auxiliary compensation system for missed seeding is more accessible to implement than a self-compensation system for missed seeding. However, since two separate seed dispersers broadcast average seeding and replanting seeds, the seed filler's installation position is strict. The optimum position of the seed filler must be obtained through theoretical derivation and practical testing, and combined with precise control algorithms for accurate replanting.

2.3.3. Work Flow and Circuit Design

A fiber optic sensor between the seed drop and the seed guide tube detects the seed discharge interval. When judging a moment of missed seeding, send the signal to the microcontroller. The microcontroller calculates the speed of the seed filler by the formula of the relationship between the working speed of the seed filler and the speed of the seed replenisher. The complementary signal is then sent down to the stepper motor driver as an electrical pulse. The stepper motor drives the seed filler at a corresponding speed of 60° to execute the seed fill command. The specific flow of the work of the compensation system is shown in Figure 7.

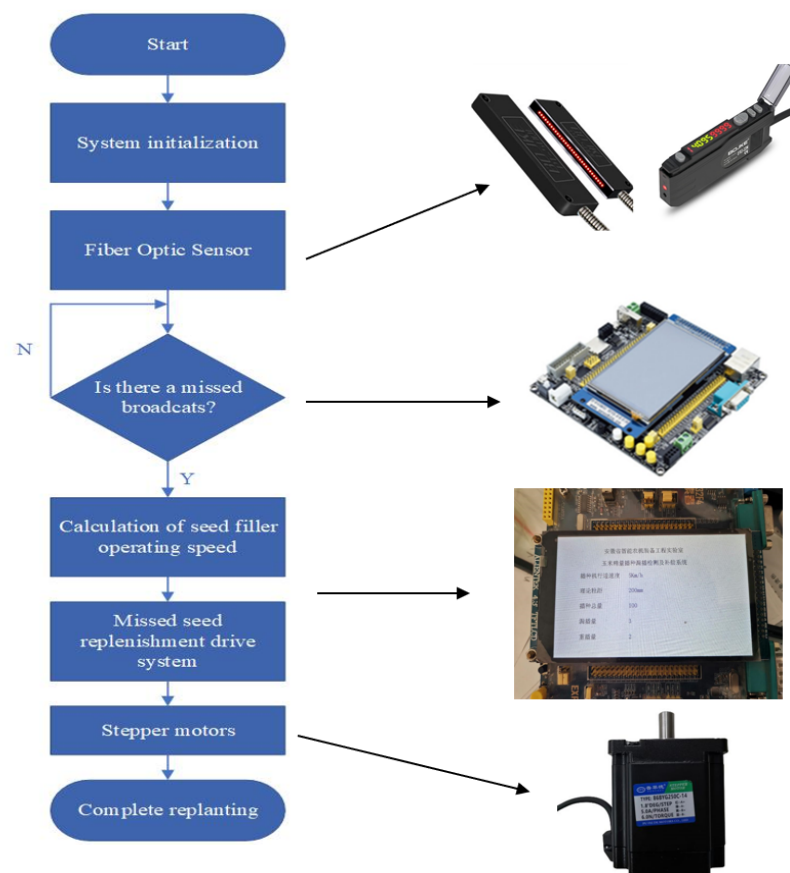


Figure 7. Work flow chart of reseeding system.

Figure 8 shows the analysis of the parameters of the replanting system. Point A in the figure shows corn seeds just passing through the seed drop of the air-suction seed dispenser. Point B is a maize seed that has just passed through the seed filler drop opening. Establish a spatial coordinate system with point O of the air-absorbing seed dispenser seed drop as the coordinate origin. The horizontal distance between point A and point B is L , and the vertical distance is h . Let the N th seed be the typical sown seed and the $N + 1$ th seed be the missed seed. The distance between the regular sown seed and the missed seed under normal sowing conditions equals the theoretical grain spacing. The seeding interval is equal to theoretical seeding interval Δt . The sensor detects a missed sowing signal after $1.5 \Delta t$ when a missed sowing occurs in the seed row.

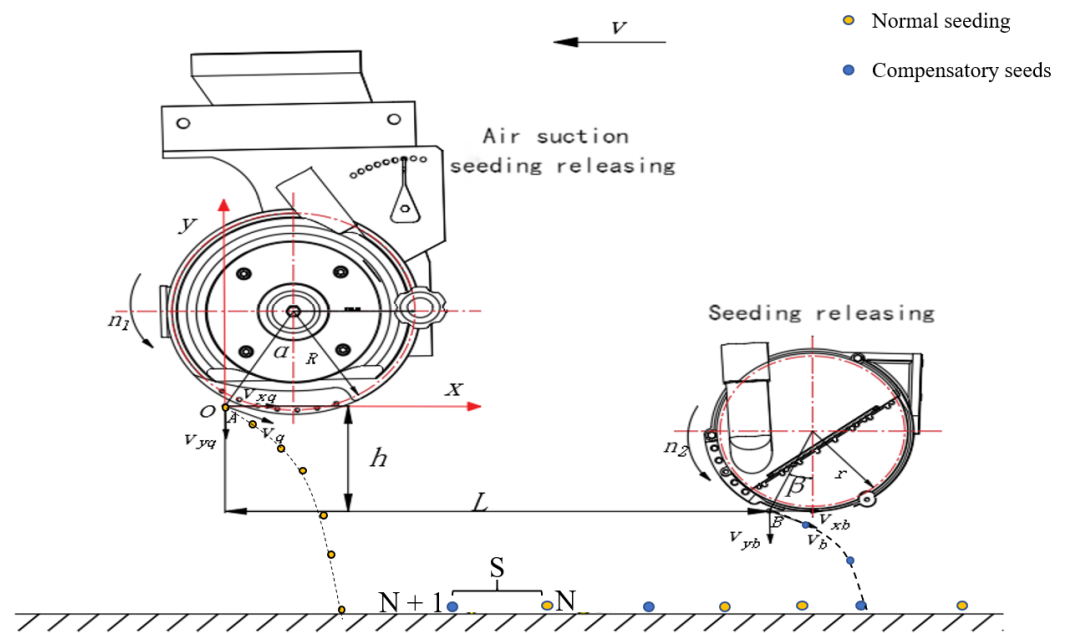


Figure 8. Parameter analysis diagram of reseeding system.

The system detects a missed seeding and starts replanting. At this point, if the $N + 1$ st seed is an ordinary sown seed, the time for point A to disengage from the seed drop is $0.5 \Delta t$. Kinematic analysis of seed A gives:

$$\begin{cases} v_{xq} = v - \cos \alpha v_q \\ v_{yq} = -\sin \alpha v_q \end{cases} \quad (7)$$

where v is the travel speed of the seeder; v_{xq} is the horizontal velocity of the seeding seed A out of the air-suction seeder's seeding opening; v_{yq} is the vertical velocity of the seeding seed A out of the air-suction seeder's seeding opening; α is the air-suction seeder's seeding angle; v_q is the air-suction seeder's seeding disc linear velocity.

In turn, the equation of the displacement coordinates of point A after $0.5 \Delta t$ can be found:

$$\begin{cases} x_q = 0.5 \Delta t (v - \cos \alpha v_q) \\ y_q = -0.5 \Delta t \sin \alpha v_q + 0.25 g \Delta t^2 \end{cases} \quad (8)$$

where x_q is the horizontal distance traveled by the sown seed A after $0.5 \Delta t$; y_q is the vertical distance traveled by the sown seed A after $0.5 \Delta t$; g is the acceleration of gravity.

If the $N + 1$ st seed is a missed seed, then the system starts replanting the $N + 1$ st seed. The seed filler starts working; then, an analysis of the point B just past the seed filler drop opening gives:

$$\begin{cases} v_{xb} = v - \cos \beta v_b \\ v_{yb} = -\sin \beta v_b \end{cases} \quad (9)$$

where v_{xb} is the partial horizontal velocity of the replenishment seed B out of the seed feeding port of the replenishment seed dispenser; v_{yb} is the partial vertical velocity of the replenishment seed B out of the seed feeding port of the replenishment seed dispenser; β is the seed feeding angle of the replenishment seed dispenser; v_b is the linear velocity of the seed disc of the replenishment seed dispenser.

Let the replanting system complete replanting after time t :

$$t = t' + \frac{10}{n_2} + A \quad (10)$$

where t is the time required for the seed replenishment system to complete the replenishment; t' is the time required for the seeds to move from the seed replasher drop port to the ground; A is the system response time.

This system uses a STM32F4 microcontroller as the controller, a fiber optic sensor as the missed seeding detection element, and a stepper motor as the replanting power drive. The response time of the whole system is less than 10 ms, and the response speed is so fast that it is negligible. Therefore, it can be obtained:

$$t = t' + \frac{10}{n_2} \quad (11)$$

Let seed B be the replanting seed for the $N + 1$ st seed, and the equation for the displacement coordinates of this seed after time t can be found as follows:

$$\begin{cases} x_b = vt - \cos\beta v_b t + L \\ y_b = -\sin\beta v_b t + \frac{1}{2}gt^2 + h \end{cases} \quad (12)$$

where x_b is the horizontal distance traveled by the replanted seed B after time; y_b is the vertical distance traveled by the replanted seed B after time.

After time t , the seeded seed A produces a new displacement coordinate equation:

$$\begin{cases} x_{q'} = 0.5\Delta t(v - \cos\alpha v_q) + vt \\ y_{q'} = -0.5\Delta t\sin\alpha v_q + 0.25g\Delta t^2 + \frac{1}{2}g \end{cases} \quad (13)$$

where $x_{q'}$ is the horizontal distance that the sown seed A moves after time; $y_{q'}$ is the vertical distance that the sown seed A moves after time.

In order to achieve precise replenishment, the replenishment seeds need to be sown exactly where the missed seeds were sown. What is also known is that the sowing position of the replant seed B needs to be the same as the sowing position of seed A. It can be derived that the displacement coordinates of the sown seed A coincide with the displacement coordinates of the replanted seed B:

$$\begin{cases} -\cos\beta v_b t + L = 0.5\Delta t(v - \cos\alpha v_q) \\ -\sin\beta v_b t + h = -0.5\Delta t\sin\alpha v_q + 0.25g\Delta t^2 \end{cases} \quad (14)$$

The optimal height of the seed filler was determined through experimental verification. The relationship between the time taken for the replanting seed to be sown into the ground from the seed drop to the speed of the replasher can be obtained:

$$t' = \frac{-2\pi n_2 r \sin\beta + \sqrt{(2\pi n_2 r \sin\beta)^2 + 2gH}}{g} \quad (15)$$

The above equation can be combined to obtain:

$$L = 0.5\Delta t(v - 2\pi n_1 R \cos\alpha) + \frac{2\pi n_2 r \cos\beta \left(-2\pi n_2 r \sin\beta + \sqrt{(2\pi n_2 r \sin\beta)^2 + 2gH} \right)}{g} + 2\cos\beta \pi r \quad (16)$$

where n_1 is the rotational speed of the air suction seeder; R is the radius of the air suction seeder disc; n_2 is the rotational speed of the seeder; r is the radius of the seeder disc; H is the vertical distance from the seed in the replacer to the sowing in the soil.

The effect of seeding height on the seeding rate was measured at seeding heights of 90 mm, 120 mm, 150 mm, 180 mm, 200 mm, and 250 mm, respectively, at a travel speed of 5 km/h, a theoretical grain spacing of 200 mm, and a seed discharge shaft speed of 23.15 r/min. The curves of the effect of the seed discharge speed and seed feeding height on the seed discharge rate of the seed discharger are shown in Figure 9.

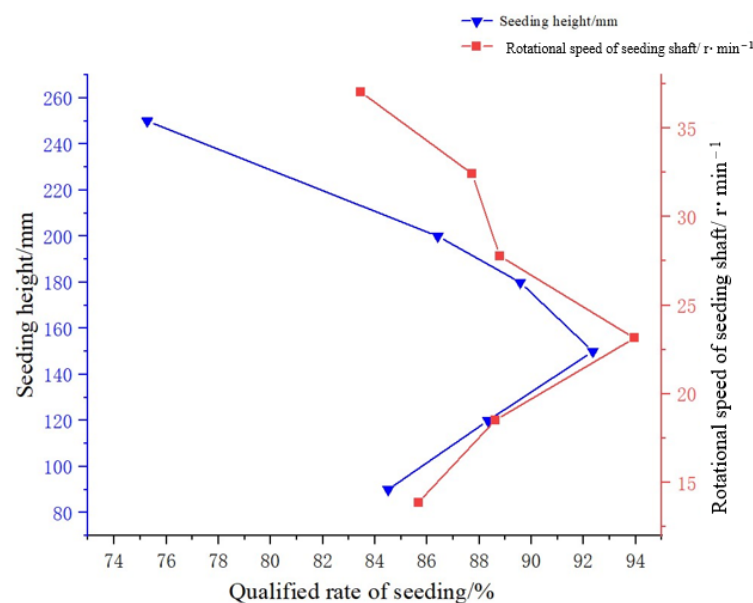


Figure 9. Seed filler performance impact graph.

It can be seen from the figure that the seed metering qualification rate of the seed metering device shows an upward trend within the range of 13.89 r/min~23.15 r/min of the seed metering shaft speed, and the highest seed metering qualification rate is 92.35% when the seed metering shaft speed is 23.15 r/min. As the rotation speed of the seed metering shaft increases, the seed metering qualification rate starts to decline. When the seed metering shaft rotation speed reaches 37.04 r/min, the seed metering qualification rate drops sharply. Therefore, the working speed of the seed metering device cannot exceed 37.04 r/min when the reseeding system is designed later. From the diagram, we can also see that the optimal seeding height of the seeding discharge device is 150 mm. Therefore, the optimal installation height of the seeding discharge device is 150 mm from the ground at the seeding discharge opening when the seeding discharge device is installed.

The best installation height of the seed filler is 150 mm above the ground, obtained through the seed filler bench test. Considering the space distribution of corn air-suction seeders and the difficulty of seed filler installation, this design chooses to install the seed filler 450 mm behind the main seeder. From the above formula, we can see that, after determining the length of h and L , the working speed of the seed filler is directly proportional to the speed of the seed discharge disc of the seed discharger. By calculating the rotation speed of the reseeding plate, the working rotation speed is obtained to realize the accurate reseeding under each sowing operation speed.

The circuit schematic design for this system uses Altium Designer, as shown in the diagram. The total system circuit diagram contains the MCU (Microprogrammed Control

Unit), the power conditioning circuit, the alarm system circuit, the fiber optic sensor circuit, the encoder circuit, the stepper motor driver circuit, and the LCD display circuit.

2.4. Bench and Field Trials

2.4.1. Bench Testing

The test material was Annong 591 maize seed, which was not graded. The test equipment mainly includes the JPS-12 seed rower performance test bench, Dahua Bolai maize air-suction precision seed rower, fiber optic sensor, tape measure, and other tools. The experimental site diagram is shown in Figure 10.

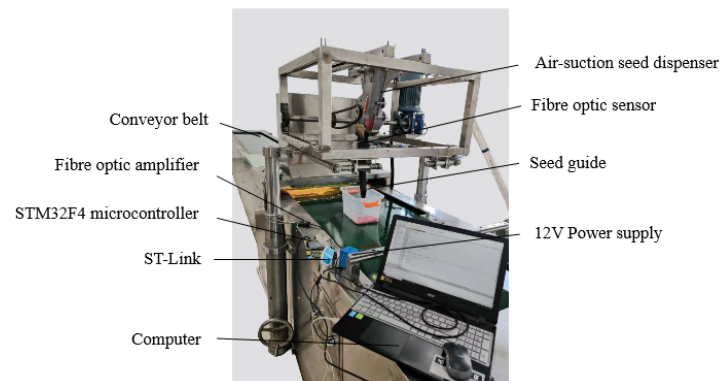


Figure 10. Test site drawing of loss sowing detection system.

Experimentation was conducted with UOBOLA air-suction seed dischargers under different operating parameters. Theoretical seed spacing is set at 200 mm, and the seeder operates at six speeds of 3, 4, 5, 6, 7 and 8 km/h. The corresponding disc speeds are 13.89 r/min, 18.51 r/min, 23.15 r/min, 27.78 r/min, 34.41 r/min, 37.04 r/min.

Specific test steps are as follows: Artificially block any two non-adjacent holes in the seeding tray, and artificially increase the rate of sowing leakage. Six sets of tests are performed at six different speeds, with each test row disc turning 10 circles. Record data on the total number of seeds sown, missed seeds, and reseeds detected by the missed seed detection system. At the same time, the computer vision system of the test stand is used to collect real-time information on the seeding process and obtain seeding data.

The test materials were selected from Jundan 20 maize seed (green seed coat) and Zhengdan 958 maize seed (blue seed coat), and the seeds were not graded. The test equipment mainly includes a JPS-12 seed row test bench, corn air-suction precision seed rower, fiber optic sensor, six scoop spoon wheel type corn rower, 86BYG250C two-phase hybrid stepper motor, DM860H stepper motor driver (Pfeiffer), voltage regulation power supply, etc. The overall test set-up is shown in Figure 11.

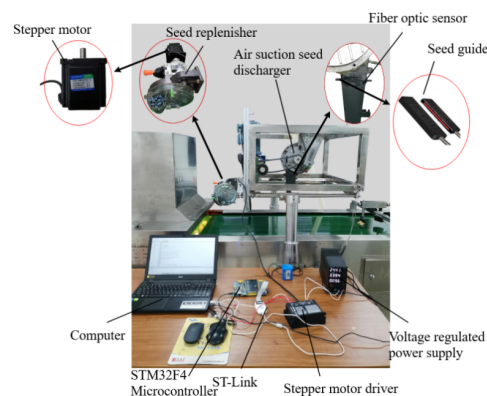


Figure 11. Corn concentrate seeding leakage detection and compensation system composition.

Adjust the negative pressure to the optimum operating conditions during the test. To distinguish between sowing and replanting seeds, dredging single 20 (green medicine coat) and Zheng dan 958 (blue medicine coat) were installed in the pneumatic exhaust box and seeding box, respectively. Seed replenishment trials were performed on Dahua Bolai seed dispensers at six different speeds. Five hundred seeds were selected as samples for each group of trials. Measurement of the sowing conformity index, the omission index, and the reseeding index was performed without and with the addition of the seed replenishment device. Simultaneous measurement of the number of seeds replenished by the replanting device and the replanting pass rate was performed. A replanting seed interval s of $0.5 S \leq s \leq 1.5 S$ between replanted and sown seeds means that the replanting is satisfactory. Figure 12 shows the sequence of seeds on the seed tape. In order to prevent the seeds from bouncing when they fall into the test stand and thus affecting the data obtained, an oil spray device was installed on the conveyor belt to simulate the seeds falling into the soil.

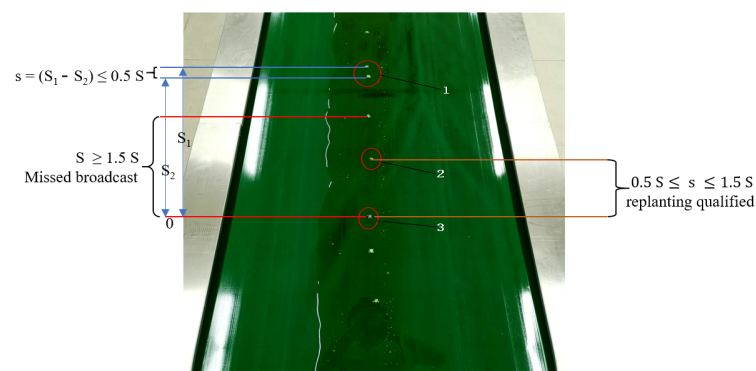


Figure 12. The seed sequence.

2.4.2. Field Trials

The ultimate goal of agricultural equipment research is to apply it to actual production. In order to verify the feasibility of the maize precision sowing missed seeding detection and compensation system designed in this paper in practical operation, field trials were conducted. The selected site was the Annon Nong Cui Garden test field, and the test plot was leveled and weeded with a land preparation machine before sowing the seeds. Jundan 20 corn seed (green seed coat) and Zhengdan 958 maize seed (blue seed coat) were used in the trial. The Dongfeng DF-1004 tractor (rated power 73.5 KW), Dahua Baolai air-suction maize precision seeder, and air-suction maize seeder were selected as the equipment for this trial. The test site is shown in Figure 13.



Figure 13. Field experiment site.

During the trial, the mulching device was removed from a group of seeding units in order to facilitate the observation of the replanting effect, and a corn precision sowing leak detection and compensation system was installed. The sowing spacing was set to 200 mm, and the tractor speed was set to 3~8 km/h. A set of tests was conducted on the seeder at different driving speeds, and the replanting was measured manually after the sowing was completed, as shown in Figure 14.

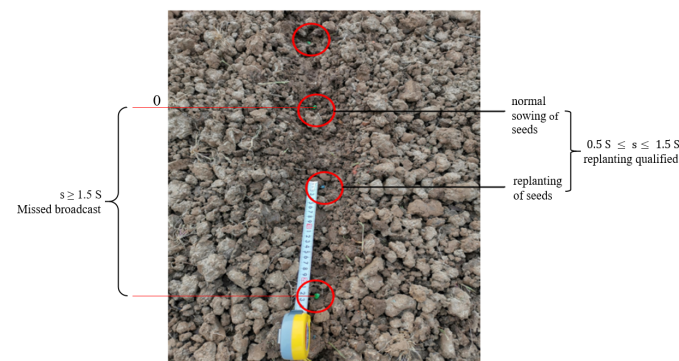


Figure 14. Test results in field.

Note: The method of measuring plant spacing shown above effectively reduces the impact of measurement errors. Seed 1 is first used as the starting point for measurement, and then the distance from seed 2 to seed 1 is measured. Continue to measure the distance from the next seed to seed 1 and then the difference with the distance from the last seed to seed 1 to obtain the distance between this seed and the last seed's plant.

3. Results and Discussion

The accuracy of a maize precision sowing miss detection system designed in this paper was verified through trials, and the seeder was tested in the field with and without a leak compensation device. It was found that the seeding pass rate was much higher for seeders installed with the missed seeding compensation system than for those not installed. It created favorable conditions for applying agricultural equipment research to practical production.

3.1. Results

This experiment was designed to test six different speed gears. The detection values of the missed seeding system and the detection values of the computer vision system were obtained. The results are shown in Table 4.

Table 4. The test results of loss sowing detection of precision sowing for corn.

Types of Seed Dispensers	Seed Discharge Shaft Speed/ $r \cdot \min^{-1}$	Measured Values for Missed Seeding Detection Systems			Measured Values from Computer Vision Systems		
		Total Seeding	Number of Missed Seeding	Rebroadcast Volume	Total Seeding	Missed Sowing Volume	Rebroadcast Volume
Dahua Bolai	13.89	240	24	4	242	25	7
	18.51	241	27	5	241	26	7
	23.15	240	25	6	240	28	8
	27.78	237	28	5	239	30	9
	34.41	232	27	4	235	32	7
	37.04	225	32	3	229	38	6

In this trial, two seed dispensers were selected and tested in the laboratory in a simulated field environment. Measurement of the total number of seeds discharged from two types of seeding discs with different numbers of holes showed that the number of type holes is 26 and 18, respectively. After blocking the two types of holes, the theoretical discharge is 240 and 160 seeds after ten weeks of rotation of the seed discharge disc. However, the standard value of the total measured seed discharge fluctuates above and below the

theoretical value due to omissions and resowing of the seed disperser. Experimental results show that missed sowing detection device has an accuracy of 96% or more of the total seed discharge. For the detection of sowing leakage, the detection accuracy is high, between 13.89 r/min and 27.78 r/min of the seed tray speed, with a maximum detection accuracy of 100% and more than 90%. When the rotational speed of the seed tray is more significant than 27.78 r/min, the accuracy of the missed seed detection starts to decrease.

The main reason is that the rotation speed of the seed metering disc increases, and the initial speed of the seed when it is discharged from the seed metering device increases, which causes the seed to hit back and forth in the seed guide tube and change the seed trajectory, thus reducing the accuracy of missed seeding detection. The detection accuracy of the missed seeding detection system for the replay is low, mainly because two overlapping seeds pass through the sensor detection area at the same time, and the sensor can only recognize the seeding signal once, or the time interval between the two seeds is less than the scanning time of the system timer, which causes the system to miss the detection of the replay.

The maize precision sowing miss detection and compensation system detects missed sowing signals at different operating parameters and makes up the seed in time. The seed filler speed is linearly related to the disc speed, so the system can calculate the appropriate seed filler speed according to the disc speed to achieve accurate seed filling.

Table 5 shows the results of the maize precision sowing miss detection and compensation system bench test—discharge disc speeds in the range of 13.89~27.78 r/min. The replanting rate of replanters is above 90%, and the pass rate of replanting is above 95%. The replanting effect decreases when the rotational speed of the seed reel is more remarkable than 27.78 r/min. The specific reason is that the seed replenisher speed is influenced and increased by the seed discharger speed. As can be seen from the previous experiments on the performance of the seed filler and seed releaser, when the operating speed of the seed filler exceeds 37.04 r/min, the seed filling performance starts to decline.

Table 5. The result of loss sowing detection and reseeding system of precision sowing for corn bench test.

Seed Dis-charger	Seed Reel Speed/(r·min ⁻¹)	Without Missed Seeding Compensation System			Adding a Missed Seeding Compensation System			Manually Measured Values			Replanting Speed/(r·min ⁻¹)
		Passing In-dex/(%)	Omission In-dex/(%)	Replay In-dex/(%)	Passing Index/(%)	Omission Index/(%)	Replay Index/(%)	Number of Missed Seedings	Number of Re-planting	Number of Eligible Replants	
Dahua Bolai	13.89	95.62	1.70	2.68	97.35	0	2.65	9	9	9	23
	18.51	94.89	2.68	2.43	97.10	0.40	2.50	13	12	11	27
	23.15	97.10	1.32	1.58	98.47	0	1.53	7	7	7	33
	27.78	94.58	2.71	2.71	96.09	0.80	3.11	14	12	10	39
	34.41	91.65	4.45	3.90	93.29	2.20	4.51	22	15	11	45
	37.04	89.53	7.86	2.61	91.75	4.80	3.45	39	25	15	53

The performance indexes of the seed metering device under different operating speeds, the seed metering disc speed, and the seed feeding height were obtained through the quadratic orthogonal test. Through the analysis of the results of the quadratic rotation orthogonal experiment, it can be concluded that when the operating speed, the rotation speed of the seed metering shaft, and the seed dropping height are 6 km/h, 22 r/min, and 130 mm, respectively, the qualified rate of sowing can reach 92.28%, and the rate of missed sowing and reseeding are 4.41% and 3.31%, respectively.

The test shows that the system has a high detection accuracy for the total seeding amount, and the detection accuracy for the missed seeding amount can reach more than 90% under the appropriate seeding parameters, meeting the precision requirements for the missed seeding detection in the seeding operation. The detection accuracy for the repeated seeding amount is not as high as the missed seeding amount.

During the trial, the mulching device was removed from a group of seeding units in order to facilitate the observation of the replanting effect, and a corn precision sowing leak

detection and compensation system was installed. The sowing spacing was set to 200 mm, and the tractor speed was set to 3~8 km/h. A set of tests was conducted on the seeder at different driving speeds, and the replanting was measured manually after the sowing was completed, as shown in Figure 15.

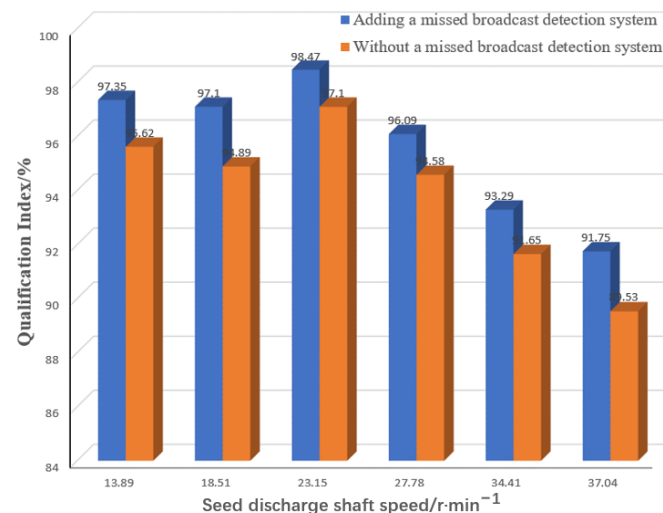


Figure 15. Analysis diagram of test results.

The test showed that, with the addition of the missed seed filler, the seeder can achieve more than a 90% seeding pass rate. The seed filler is used to improve the qualification rate by about 7–10% compared to the non-seed filler. The figure shows that the replanting grain spacing is controlled between 0.5 times the theoretical grain spacing and 1.5 times the theoretical grain spacing, which meets the requirement of missed replanting. The feasibility and reliability of this design for the detection and compensation of missed maize precision sowing can thus be concluded.

Table 6 shows the field experiment results of the detection and compensation system for missed sowing of corn. In order to verify the effect of the detection system visually, under similar conditions to the bench experiment, it is verified that the detection and compensation system for missed sowing of corn has a good effect in the field. The system can detect the missed seeding signal in the complex field environment and reseed in time. The speed of the reseeding device calculated by the system is consistent with the bench experiment.

Table 6. Shows the results of field trials of the missed seeding detection and compensation system.

Seed Dis-charger	Seed Reel Speed/(r·min ⁻¹)	Without Missed Seeding Compensation System			Adding a Missed Seeding Compensation System			Manually Measured Values			Replanting Speed/(r·min ⁻¹)
		Passing In-dex/(%)	Omission In-dex/(%)	Replay In-dex/(%)	Passing In-dex/(%)	Omission In-dex/(%)	Replay In-dex/(%)	Number of Missed Seedings	Number of Re-planting	Number of Eligible Replants	
Dahua Bolai	13.89	87.02	5.61	7.37	92.94	0.19	6.87	28	27	27	23
	18.51	89.74	5.96	4.30	94.80	0.85	4.35	30	28	26	27
	23.15	92.67	4.00	3.33	96.41	0.43	3.16	20	18	18	33
	27.78	89.46	7.14	3.40	95.03	1.00	3.97	34	30	29	39
	34.41	83.61	10.24	6.15	90.31	2.43	7.26	49	45	37	45
	37.04	81.85	12.55	5.60	88.67	3.47	7.86	58	53	41	53

It can be seen from Figure 16 that the qualification rate of the missing seeding detection and compensation system installed in the field test is higher than that of the system not installed, which effectively reduces the missing seeding index of the seed metering device. At the same time, in the range of 13.89~27.78 r/min, the qualified reseeding rate can also be kept above 90%, and the highest rate can reach 96.41%. When the rotation speed of the

seed metering plate is more remarkable than 27.78 r/min, the effect of reseeded is reduced, which is consistent with the bench test results. The design of the missed seeding detection and compensation system is reasonable.

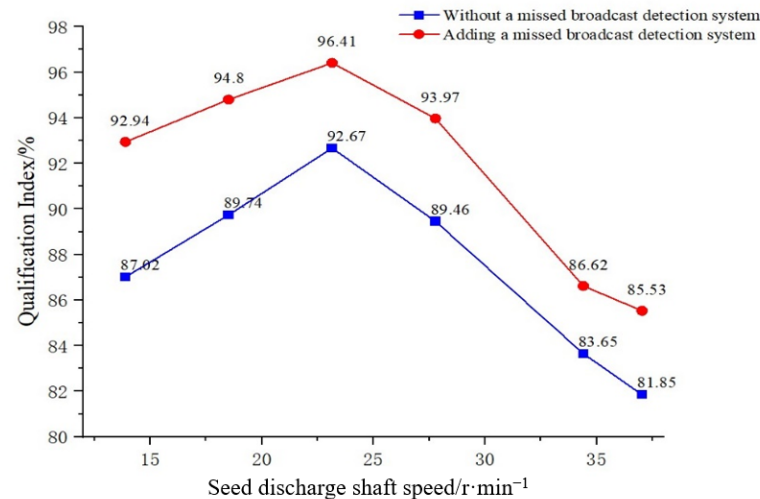


Figure 16. Analysis chart of field test results.

3.2. Discussion

Conventional seeders suffer from a lack of seed in the seed box, clogging of the seed tray and the seed guide tube, and slippage of the ground wheel. These causes contribute to missed sowing, which dramatically affects maize yields. This paper addresses the phenomenon of missed sowing during maize planting. A method for detecting and compensating for missed seeds in maize precision sowing uses a maize air-suction seeder as the research object. They were using fiber optic sensors to detect missed seeds during maize sowing. A MSCS was designed to address the difficulties in replenishing maize seedlings later.

For the maize precision sowing leakage detection and compensation system designed in this paper, further in-depth research can be conducted in the following aspects. In an in-depth study of the effect of seed guide tubes on seeding, the seed guide tube in this design provides easy installation of the fiber optic sensor but affects the seed drop trajectory. Especially when the operating speed increases, it causes the error between the sensor detection value and the actual value to increase. The maize precision sowing missed sowing detection and compensation system only achieves an alarm for continuously missed sowing, and the method of continuous missed sowing replenishment should be researched later. Regarding the smaller design of the seed filler, although the six-scoop wheel seed metering device selected in this design has a compact structure, it is bulky after being connected to the stepping motor due to its gearbox. Therefore, it is possible to design a future reseed device with a more compact structure and more convenient installation. Optimizing the stepper motor speed algorithm, the stepper motor can adjust the speed of the seed filler according to the change in the operating speed of the seed filler, but the algorithm is relatively simple and can be further optimized to make the seed filler more accurate.

4. Conclusions

A method for detecting missed seeding in maize precision sowing is proposed, taking a maize air-suction seeder as the research object. The maize precision sowing miss detection system was developed and bench-tested, providing a system to compensate for missed sowing of maize seeds and the difficulty of replanting at a later stage. The components and operating principles of a maize precision sowing detection and compensation system are

defined, and validation trials of a missed seeding detection and automatic compensation system are conducted

Based on the analysis, comparison, research, and trials, the following conclusions were drawn:

1. Bench tests showed that the leak detection system can detect more than 96% of the total number of seeds discharged. For the detection of sowing leakage, the seeding disc speed is between 13.89 r/min and 27.78 r/min. Showing high detection accuracy, the highest detection accuracy can reach 100% and basically can reach more than 90%. When the seeding disc speed is more excellent than 27.78 r/min, the accuracy of the missed seeding detection starts to decrease.
2. The seed filler bench test resulted in an optimum seed filler mounting height of 150 mm and a critical operating speed of 37.02 r/min. Experiments on stepper motor speed and angular accuracy were conducted. It is concluded that the step motor speed error is below 0.3%, and the corner error is below 4%, which meets the accuracy requirements of the leakage compensation system.
3. Defined system components for detecting and compensating for missed seeding in maize precision sowing were described. The system consists of four main components: detection system module, control system module, display system module, and actuation system module. The experimental results showed that the seed discharge disc speed ranges from 13.89 r/min to 27.78 r/min. The replanting rate of replanters is above 90%, and the pass rate of replanting is above 95%. When the rotation speed of the seed reel is greater than 27.78 r/min, the seed replenishment rate and the seed replenishment pass rate are reduced. The two seed dispensers were equipped with a missed seeding compensation system at speeds between 13.89 and 27.78 r/min. None of the missed seeding indices exceeded 1%. The maximum qualifying index of Dahua Bolai seeding can be raised to 98.47%, and the maximum qualifying index of Nonghaha seeding can be raised to 96.41%. When the rotational speed of the seed reel is greater than 27.78 r/min, the seed replenishment effect is significantly reduced.

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