

Realization of an integrated seeding and compensating potato planter based on one-way clutch

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Abstract: The yield reduction caused by miss-seeding in potato mechanized sowing is astonishing. The existing research always needs to install a spare compensator on the original seed-metering device. Therefore, problems of complex planter structure and compensated potato seed poor landing accuracy need to be solved urgently. Consequently, a scheme of integrated seeding and compensating potato planter based on one-way clutch is proposed in this paper. Based on a basic 'improved one raw potato planter' and the working principle of one-way clutch, power of seed-metering system is provided through main power transmission one-way clutch by land wheels when the system works properly. However, when miss-seeding detection system with infrared radiation deciding that a miss-seeding incident has happened, the seed-metering power will be replaced by a compensatory motor through compensating one-way clutch at a higher speed. Thus, the idea of catching-up compensation can be realized. After compensation is completed, the system controller disconnects the compensatory motor, and the seed-metering power will naturally switch to the land wheels again. A prototype based on this idea was built. Field tests showed that the accuracy of seed monitoring system is more than 99.9%; the adoption of catching-up compensation scheme does not bring about empty spoon rate rise significantly. Within the range of 0.2-0.8 m/s of the seed-metering chain speed, although the average success compensation rate decreases evidently with the increase of the chain speed, the success compensation rate is still near 70% even at 0.8 m/s, the vast majority of missed seeds can be compensated effectively.

Keywords: potato planter, infrared radiation miss-seeding detection, one-way clutch, catching-up compensation

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1 Introduction

Mechanized sowing is the key link of large-scale potato planting and the basis of its mechanized harvesting, seed-metering device is the core of potato planter, and its performance directly affects the quality and efficiency of seeding operation^[1-3]. However, due to natural variations of cutting potato seeds of the shape, size and poor fluidity, it's hard for them to be taken into seed scoops^[4-6]. Miss-seeding will lead to congenital yield reduction. Taking Chinese potato planting data in 2017 for

example, China's area is about 5.67 million hm², and the yield is 96 million t, ranking first in the world^[7]. If just calculated by 5% miss-sowing rate, the output reduction would beyond 4.8 million t, which is equivalent to a standard food quota for a developing country with a population of 2.4 million for one year. Similar reductions in worldwide will be even more alarming. So it is urgent to study theories and techniques to avoid or reduce miss-seeding during potato's mechanical seeding.

To address miss-seeding, the simplest way is artificial reseeded^[8-10]. This method is not only labor intensive but also inefficient. The success rate and reliability are low and the cost increase is considerable. The miss-seeding rate can also be reduced by improving the structure of potato planter. This approach can reduce the miss-seeding rate but often requires complex systems. Even so, the improved seed-metering device still has a miss-seeding rate of about 5%^[11-13]. An effective way to solve this problem is to add detection and automatic compensation devices on potato planter^[14]. This is actually part of the booming Precision Agriculture, which is precisely in the category of Precision Sowing^[15-18].

Pursuit of precision sowing has a long history. As early as the 1940s, European and American countries have taken the lead in developing precision seeding machines for traditional bulk crops, such as corn, soybean, etc. These crops had been able to sow precisely for a long time^[19,20]. However, due to the fact that potato cultivation in Europe and the United States is dominated by whole-potato seeds and large-scale machinery, the miss-seeding is

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not a serious problem there. However, due to the large population and the shortage of land resources, China is the real driving force for the study of potato miss-seeding control. However, the research and development efforts associated with precision sowing in China are mainly focused on wheat^[21], rapeseed^[22] and alike. There are also studies on the position-unbiased replenishment system for large-grain crops^[23,24]. These miss-seeding monitoring and compensation schemes are effective with the grain crop seeds, however, they are not directly applicable to potato planter. In China, the existing research and development efforts in potato seeding monitoring are mainly based on seed-metering/tube monitoring. It is necessary to install a spare compensator on the original seed-metering device when the original device fails to sow, the compensation device can supplement in time. For example, Zhang et al.^[25], Sun et al.^[26] and Wang et al.^[27] proposed to use infrared irradiation for miss-seeding detection, which has a high accuracy; the compensation schemes they adopted, however, are not mature for wide applications. Among them, the fast-moving hit device is easy to be blocked in the entrance of compensating seeds^[26], while the external groove wheel seed-metering device was found potato seeds can be damaged occasionally^[27]. The detection scheme of potato miss-seeding based on the capacitive sensor^[28] is feasible in theory, however, its reliability needs further proof. Potato air-suction seeding is a new technology adopted in recent years^[29,30]. The precision seed suction and metering under negative and positive pressure separately with synchronized actions of blowers and suction fans, the position accuracy and the speed of potato sowing have improved. However, the potato air-suction seeder has a higher technical requirement and even more complex structure, it is also more expensive and difficult to be maintained. Therefore, it is still far away from popularization.

It can be seen from the above overview, only seeding monitoring system is relatively mature, but its reliability still needs to be further improved in practice. Moreover, the above-mentioned detection and compensation schemes for miss-seeding are just in laboratory, so far, no mature commercial products have been found in market. Obviously, for potato precision sowing with small and medium-sized machines, the main technical obstacles are still the difficulty of miss-seeding detection and the difficulty of compensation execution. In line with the principles of cost control, technology risk reduction, simplicity and efficiency, a kind of integrated seeding and compensating potato planter based on one-way clutch is proposed in this paper. It has a unique structure, additional motion channels for compensating seed potatoes is not required, attached compensating seed tank is unnecessary neither, and can easily be controlled, potato miss-seeding can be significantly inhibited.

2 Structure and system controller of the new potato planter

2.1 Functional requirement analysis and new scheme

No special compensating potato seeds motion channel, which requires the same channel for seeding and reseeding, and it is necessary to speed up the later seed to catch up with the missed ahead. Therefore, other external power is needed to drive seed-metering chain. After compensation, the external power must be able to withdraw in time automatically. Therefore, based on one-way clutch, a scheme for a kind of integrated seeding and compensating potato planter is shown in Figure 1.

Based on an 'improved one raw potato planter' and the principle of one-way clutch, power of the seed-metering system is

provided through the main power transmission one-way clutch by the land wheels under normal conditions as illustrated by Figure 1. When miss-seeding occurs, the power of the seed-metering system will be replaced by the electric motor through the compensating one-way clutch at a higher speed of the seed-metering chain. After compensation is completed, the system controller closes the power supply of the electric motor, then, the power of the seed-metering system switches to the land wheels again. A defining advantage of the new scheme is that it does not have a separate compensation potato tank or a separate motion channel for compensatory potato seeds. Instead, it utilizes an automated mechanism that accelerates the latter potato seed (when it can) in the main seeding channel. The structure of the new machine is simpler, and the position accuracy of the compensating potatoes can be improved through the software optimization of the system controller.

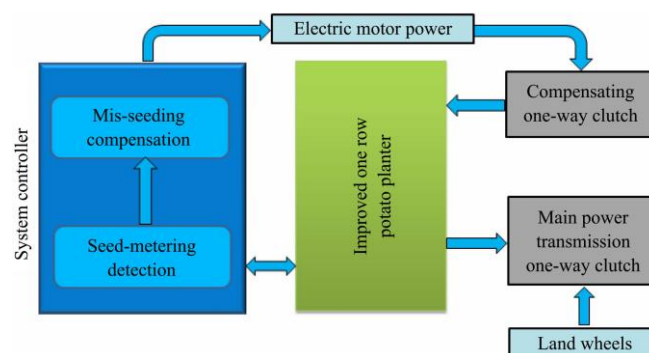


Figure 1 Scheme diagram of the integrated seeding and compensating potato planter

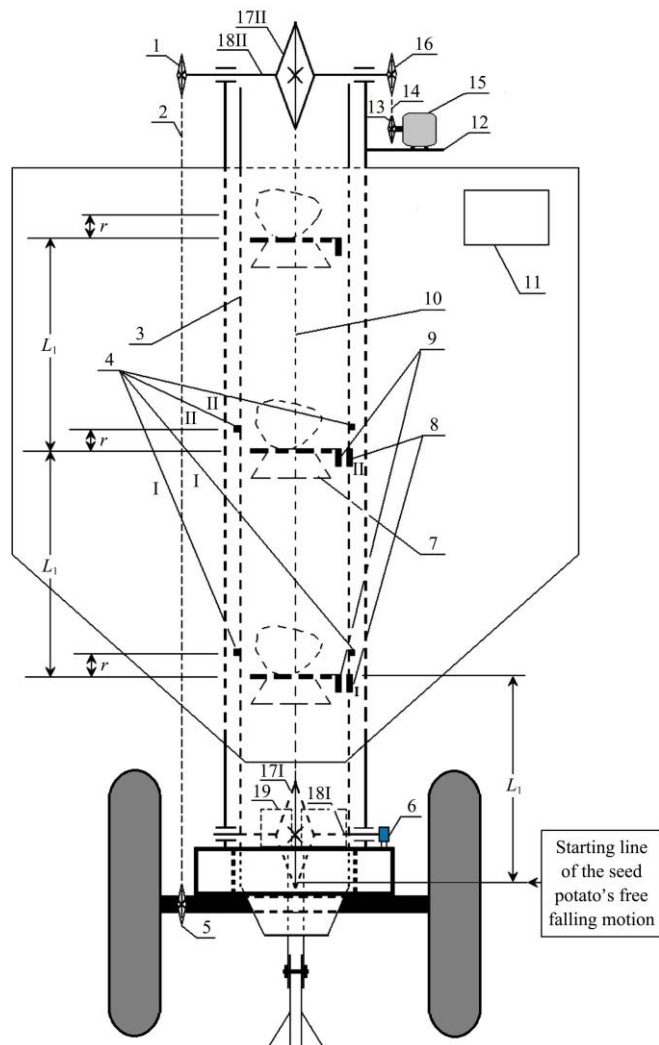
2.2 Structure of the potato planter

The integrated seeding and compensating potato planter based on one-way clutch includes four subsystems: improved one raw potato planter, miss-seeding detection system, miss-seeding compensation system based on one-way clutch and system controller. The structure of this new kind of potato planter is shown in Figure 2.

As shown in Figure 2, first pay attention to land wheels and land wheels axle, which are driven by tractor in field providing platform support for potato planter. The lower and upper ends of the seed-metering groove are provided with seed-metering chain wheel axle (I, II), respectively. The seed-metering chain wheels (I, II) are set separately on the seed-metering chain wheel axles (I, II) individually. The seed-metering chain is hung between the seed-metering chain wheels with a number of seed spoons evenly arranged on the chain. The main power transmission one-way clutch is installed on one side of the seed-metering chain wheel axle II. Through the main power transmission chain wheel and the land wheel power transmission chain, the power on the land wheels axle reaches the seed-metering chain wheel axle II.

For the miss-seeding detection system, each seed spoon is instrumented with a seed spoon position signal carrier at the same side position. The seed spoon position sensors (I, II) are placed at the corresponding sides of each seed spoon position signal carriers on the seed-metering groove. The distance between the adjacent seed spoon position sensors is set to L_1 . Meanwhile, the distance between the seed spoon position sensor I and the Starting line of the seed potato's free falling motion is also set to L_1 . On the horizontal plane with a distance r (the average radius of the cutting potato seeds) from the seed spoon position sensors (I, II), photoelectric sensor set for seed-metering detection (I, II) are

instrumented respectively; I is for miss-seeding detection and II is for compensatory potato seeds availability determination. The seed spoon position sensors and the photoelectric sensors are connected to system controller. The configuration of miss-seeding compensation system based on one-way clutch is directly driven finally by the torque of seed-metering chain wheel axle II via compensating one-way clutch, power transmission chain for miss-seeding compensation and electric motor power output chain wheel from electric motor. Speed of seed-metering chain wheels (I, II) is obtained from velocity encoder, and based on which, the real-time seed-metering chain velocity can be calculated.



1. Main power transmission one-way clutch 2. Land wheel power transmission chain 3. Seed-metering groove 4. Photoelectric sensor set for seed-metering detection (I, II) 5. Main power transmission chain wheel 6. Velocity encoder 7. Seed spoon 8. Seed spoon position sensor (I, II) 9. Seed spoon position signal carrier 10. Seed-metering chain 11. System controller 12. Electric motor mounting base plate 13. Electric motor power output chain wheel 14. Power transmission chain for miss-seeding compensation 15. Electric motor 16. Compensating one-way clutch 17. Seed-metering chain wheel (I, II) 18. Seed-metering chain wheel axle (I, II) 19. Electric motor driver

Figure 2 Structure of the integrated seeding and compensating potato planter

2.3 The system control scheme

Schematic of the system control of the integrated seeding and compensating potato planter (cf., Figure 2) is shown in Figure 3. The keyboard, data display and CPU provide the human-computer interaction interface for parameter setting and machine operation. The reset button provides system clearance, emergency shutdown

and system restart functions. With signals from seed spoon position sensors, photoelectric sensor sets and velocity encoders, CPU can then make judgment on whether miss-seeding occurs. When miss-seeding is detected, CPU sends out signals to engage the one-way clutch and to activate the electric motor driver, and miss-seeding alarm can be set off by sound-optic circuit if it is needed. The electric motor will drive the seed-metering chain (identified as #10 in Figure 2) to the required speed for compensation. Essentially, during the compensation, power source for the seed-metering system will be switched from the land wheels to the electric motor. At the same time, the numbers of N_1 , N_2 , N_3 , and N_4 are counted and the results are updated real time on data display. At the end of the compensation, CPU sends out a control signal to stop the electric motor. Power of seed-metering system is detached from the compensating one-way clutch and returns to the land wheels. Vehicle batteries are used to power the system controller, all the sensors, the velocity encoder, the electric motor driver and the electric motor.

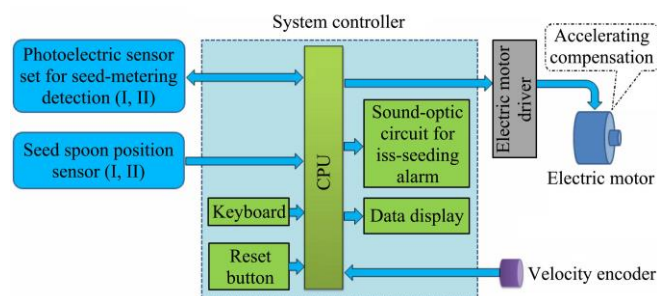


Figure 3 System control scheme diagram

3 Miss-seeding compensation control rules

As discussed earlier, under normal working conditions, power of the rotating land wheel axle is transmitted to the seed-metering chain wheel axle II, system controller counts and displays natural sowing number N_1 based on sensor signals from the seed spoon position sensor (I, II) and the photoelectric sensor set for seed-metering detection (I, II).

When the seed spoon position sensor indicates that a seed spoon arrives at the seed spoon position sensor I, CPU sends signals to trigger the photoelectric sensor set for seed-metering detection I to work. When any of the receivers of the photoelectric sensor set for seed-metering detection I shows no change of signals over a predetermined period of time, it means that the seeds on the passing seed spoon do exist. Otherwise, if each of the receivers shows a pre-determined signal change, it indicates there will be a miss-seeding. The same procedure and algorithm were implemented for the determination of availability of compensatory potato seeds using the signals from seed spoon position sensor II and photoelectric sensor set for seed-metering detection II. The sequence of the events can be illustrated in Figure 4.

Figure 4a shows the event when missed potato seed is detected at spoon #③ and a compensatory seed is detected at spoon #④ (left), seed-metering chain speed is increased from vehicle wheel driven speed v_1 to compensating one-way clutch accelerated speed v'_1 , and the compensatory seed is being planted (center). After the compensation, the speed of seed-metering chain returns to v_1 (right). Under this scenario, the compensatory potato seed would reach the position planned for the missed seed. The sequence of the potato seeds is illustrated at the bottom of Figure 4a. Therefore, this control can be called Catching-up Compensation.

However, for another example, if a missed potato seed (spoon #③) and followed by an unavailable one on the consecutive spoon (#④), the compensation scheme will result in a missed seeding and followed by a deviation of seed location as illustrated at the bottom of Figure 4b. In this scenario, the one-way clutch will be activated and compensation seed would come from the spoon #⑤.

A more serious incident is that a missed potato seed (spoon #③) and followed by two consecutive empty spoons (spoons #④ and #⑤), e.g., as illustrate by Figure 4c. The one-way clutch will be activated too, but, two missed sowings will be inevitable as shown at the bottom of Figure 4c.

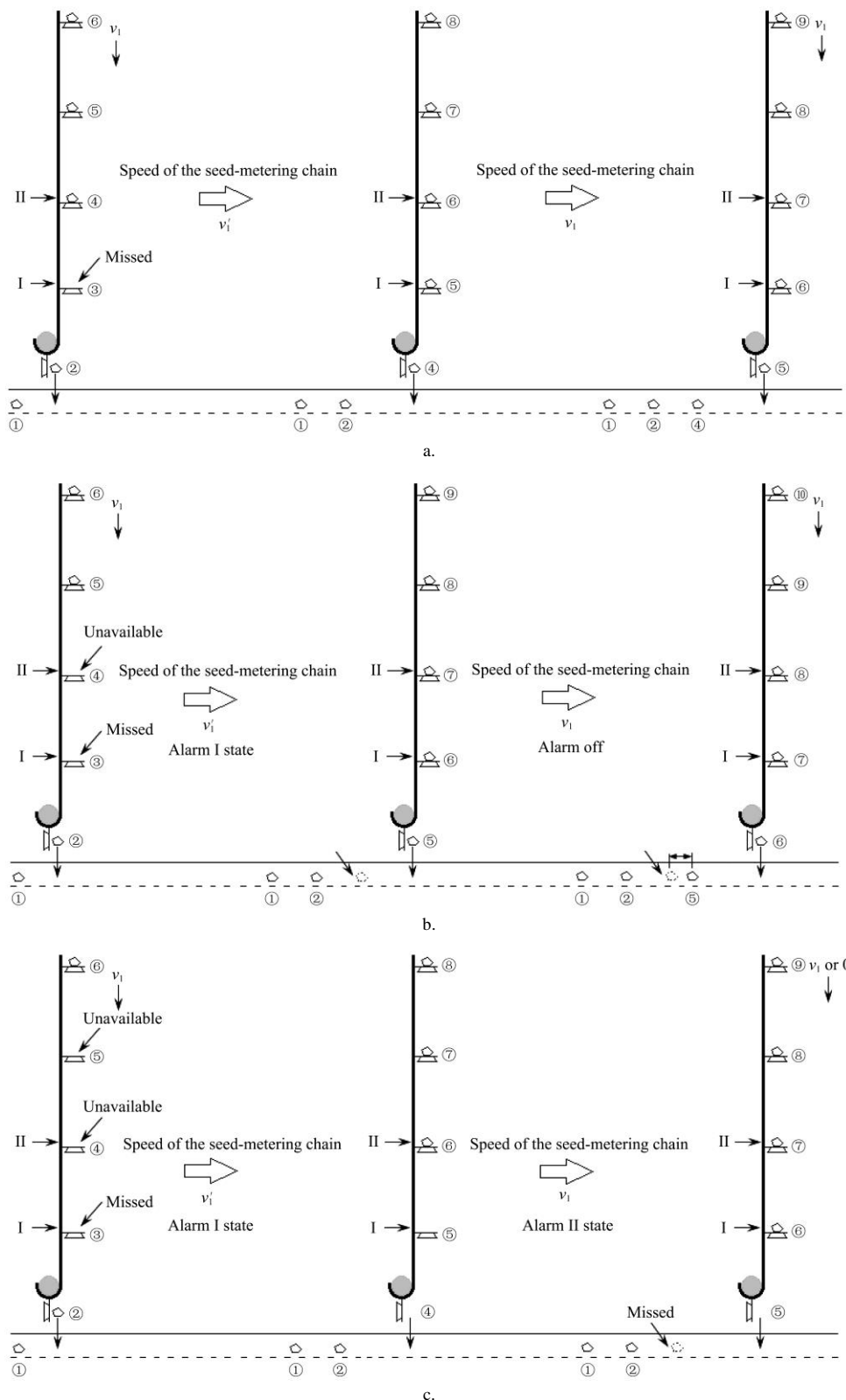


Figure 4 Miss-seeding compensation control schemes

It is noted that when a missed seed on spoon is detected, e.g., spoon #③ in Figure 4a and a potato seed is present in subsequent spoon, spoon #④ in Figure 4a, CPU will send signals that engage

the one-way clutch for the electric driver to take over the seed-metering chain driven. The seed-metering chain speed is increased to v_1' and the compensation system will implement

sowing with a zero falling compensation. However, when no potato seed is detected in subsequent spoon (e.g., spoon #④), CPU will trigger the sound-optic circuit for miss-seeding alarm on alarm I state. At the same time, the one-way clutch is engaged, and compensation potato seed will come from spoon #⑤. When this scenario occurs, it will result in a non-zero falling-point deviation compensation as illustrated by Figure 4b. The control algorithm will switch metering chain power back to land wheels and set the alarm off after the compensation. Otherwise, it can be found from Figure 4c that, when there are two additional missing seeds in spoons #④ and #⑤, CPU will send out alarms I and II one after another. When alarm II is set off, the electric motor is powered off automatically, and the tractor output power should be shut down as soon as possible at this time. It must be emphasized that, for the first, the alarm II can only be turned off manually, and then, the seed-metering system needs careful check and/or repair before it will be restarted again.

4 Kinematics and mechanism of prototype potato planter

Based on the structure of the integrated potato planter as shown by Figure 2, and the control system architecture is shown in Figure 3, and the miss-seeding compensation principle described above, the kinematic and mechanism of the integrated planter is described in this section.

4.1 Parametric relations under normal conditions

The distance between the adjacent sowed potatoes, L , is determined by the structure of the mechanical system. Under the normal condition, the system controller does not perform additional control work except counting the natural sowing number, N_1 , and updating it on the data display. As discussed earlier, power of the seed-metering system is provided through the main power transmission one-way clutch by the land wheels. The metering-chain speed is given by Equation (1)

$$v_1 = \omega_1 R \tag{1}$$

4.2 The electric motor angular speed under compensation

When miss-seeding is detected, the seed-metering chain is accelerated, it will lead to a displacement of $2L_1$ under the scenario

depicted in Figure 4a. Under this condition, the speed of seed-metering chain must achieve $2v_1$ with the force of electric motor by the compensating one-way clutch. Therefore, there is

$$v'_1 = 2v_1 \tag{2}$$

This action is accomplished by a gear angular speed ratio n_2/n_1 between the compensating one-way clutch (#16, Figure 2) and the electric motor power output chain wheel (#13, Figure 2). The angular speed of the electrical motor under compensation can be calculated to be

$$\omega' = \frac{2n_2}{n_1} \omega_1 \tag{3}$$

4.3 Correction expression of the relevant result in 4.2

In view of the specific compensation control scheme adopted, the angular speed ω' of the electrical motor and the run time t_1 are the two most important parameters required. However, the execution of the CPU command and the electrical motor response time to reach the set angular speed, in Equation (3), an empirically-determined motion compensation coefficient, K_1 , needs to be taken into account. The corrected Equation (3) is

$$\omega' = K_1 \frac{2n_2}{n_1} \omega_1 \tag{4}$$

The motor run time is

$$t_1 = \frac{L_1}{\omega_1 R} \tag{5}$$

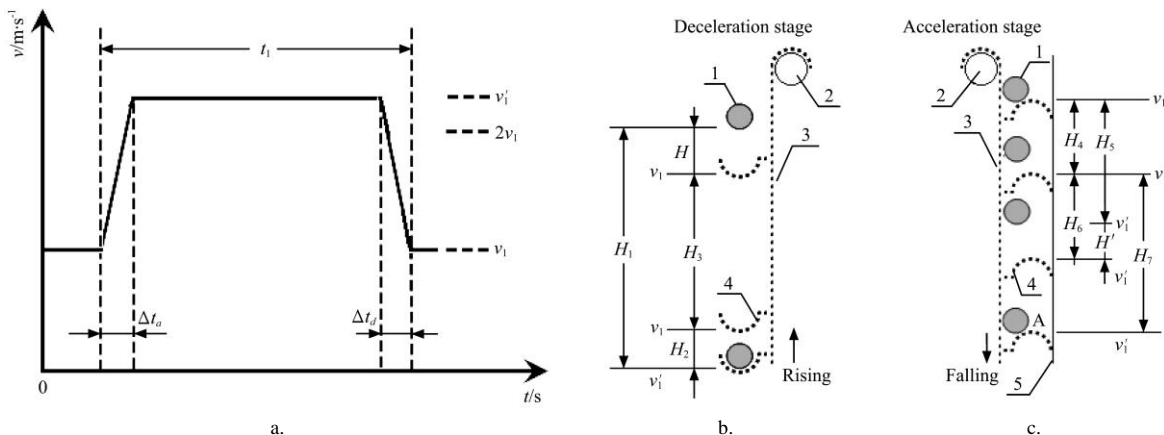
Correspondingly, the speed of the seed-metering chain during seed compensation of the scenario Figure 4a is

$$v'_1 = 2K_1 \omega_1 R \tag{6}$$

The control strategy set by Equations (4) and (5) is to ensure zero falling-point deviation for scenario of Figure 4a that the tractor speed stays the same during the compensation. However, the situations are shown in Figure 4b and Figure 4c are also based on Figure 4a, and no further analysis is needed.

4.4 Seed and system stability analysis

There is a typical process of acceleration and deceleration in each potato miss-seeding compensation, moreover, rapidity is an important index. Therefore, the stability of potato seed in spoon and the compensation control system are very important.



1. Potato seed 2. Seed-metering chain wheel II 3. Seed-metering chain 4. Seed spoon 5. Seed-metering groove
Figure 5 Seed-metering chain speed control in a typical compensation

First of all, the stability of potato seed is closely related to the speed control strategy of seed-metering chain in compensation. The speed control process of the seed-metering chain in a typical miss-seeding compensation can be shown in Figure 5a. Where t_1 represents the total compensation time consumption, while Δt_a and Δt_d represent time length of the acceleration and deceleration stage

respectively. The speed of spoon rate in the rising and falling sections is the same as that of seed-metering chain in Figure 5a, only at the lower and upper rotating shafts (i.e. corresponding to seed-metering chain wheel I, II respectively), the speed of the seed spoon is faster than that of the seed-metering chain. There is seed protection net above the seed-metering chain wheel II, and the

seeds cannot fly out; at the seed-metering chain wheel I, some spoons are covered in the seed-metering groove, some are immersed inside potato seeds, and the stability of seeds on the spoons are not involved either. Therefore, the stability of potato seeds just in the rising and falling sides that needs to be considered. Based on the working principle of the system, potato seed during the deceleration stage on the rising side may fly vertically away from seed spoon, as shown in Figure 5b. Similarly, potato seed during the acceleration stage on the falling side may also fly away from the back of seed spoon in vertical direction, see Figure 5c.

According to Figure 5b, H_1 is the distance from the initial position of the seed in Free Falling Movement from v'_1 to v_1 , H_2 is the displacement from the initial position of the seed to the starting point of uniform motion under v_1 , H_3 is the space of seed spoon running at v_1 during the time period after subtracting H_2 from H_1 . Therefore, H is the maximum gap of seed potato that can fly away from the seed spoon. The specific calculation is as follows,

$$H_1 = v'_1 \left(\frac{v'_1 - v_1}{9.8} \right) - \frac{1}{2} g \left(\frac{v'_1 - v_1}{9.8} \right)^2 \tag{7}$$

$$H_2 = v'_1 \Delta t_d - \frac{1}{2} \left| \frac{v'_1 - v_1}{\Delta t_d} \right| (\Delta t_d)^2 \tag{8}$$

$$H_3 = v_1 \left(\frac{v'_1 - v_1}{9.8} - \Delta t_d \right) \tag{9}$$

$$H = H_1 - H_2 - H_3 \tag{10}$$

It is only needed to consider the most serious situation here. The required data are $v'_1=1.65$ m/s, $v_1=0.8$ m/s, $g=9.8$ N/s², $\Delta t_d=0.1t_1=2L_1/(2v_1)$, $L_1=0.114$ m. According to Equations (7)-(10), it can be calculated that $H_{max}=30.8$ mm. However, the depth of spoon is 15 mm. Therefore, under the above conditions, potato seeds can fly away from the seed spoon indeed. However, this is the most serious case, and in the vertical direction, even this distance is generally not enough to make the seed out of its track. Soon, the seed will return to the seed spoon again. For other cases, such as $v'_1=1.23$ m/s and $v_1=0.6$ m/s, there will be $H_{max}=14.3$ mm. Obviously, this is a very safe value, potato seed has no possibility to fly away from the seed spoon.

Similarly, in Figure 5c, H_4 is the advance distance of seed spoon for compensation acceleration from v_1 to v'_1 , H_5 is the displacement from the initial position of the seed in Free Falling Movement from v_1 to v'_1 , H_6 is the distance for seed spoon to move forward after H_5 time minus H_4 time, when the system is in compensating uniform motion at v'_1 . Therefore, H is the maximum drift of seed potato that can fly away from the back of seed spoon in vertical direction. The relevant calculation is as follows,

$$H_4 = v_1 \Delta t_a + \frac{1}{2} \left(\frac{v'_1 - v_1}{\Delta t_a} \right) (\Delta t_a)^2 \tag{11}$$

$$H_5 = v_1 \left(\frac{v'_1 - v_1}{9.8} \right) + \frac{1}{2} g \left(\frac{v'_1 - v_1}{9.8} \right)^2 \tag{12}$$

$$H_6 = v'_1 \left(\frac{v'_1 - v_1}{9.8} - \Delta t_a \right) \tag{13}$$

$$H' = H_4 + H_6 - H_5 \tag{14}$$

Also, consider the maximum operating speed, but $\Delta t_a=0.1t_1=2L_1/(2v_1)$ at this time, so it can be obtained that $H'_{max}=30.8$ mm. Is this potato seed which is vertically away from seed spoon H' able to return to its original position in this compensation cycle? In order to answer this question, it is needed to assume that when the speed of the seed spoon is accelerated to v'_1 and continues to move down at this uniform speed lasts for t_m s, the potato seed will fall

back to its initial position, and the height drop of the seed spoon in this period of time is H_7 , it means that

$$H_4 + v'_1 t_m = v_1 (\Delta t_a + t_m) + \frac{1}{2} g (\Delta t_a + t_m)^2 \tag{15}$$

From Equation (15), it can be got

$$t_m=0.1518 \text{ s}$$

Then, because

$$\Delta t_a + t_m > t_1 \tag{16}$$

Therefore, t_m and H_7 are impossible to achieve, and under the most severe situation, the potato seed that drifts as shown in Figure 5c can only be forced to terminate by deceleration stage, without any potato seed landing deviation. Based on this, another influence can not be ignored. That is, when the potato seeds return to point A shown in Figure 5c, the initial velocity v_A caused by the gravitational acceleration is,

$$v_A = v_1 + g t_1 \tag{17}$$

while the seed spoon at point A has been shifted to the uniform motion velocity v_1 , so the velocity impact Δv_A at point A is

$$\Delta v_A = v_A - v_1 \tag{18}$$

Continue to be subject to the maximum operating speed parameters, it is known that $v_A=2.1965$ m/s, and $\Delta v_A=1.3965$ m/s. In theory, this velocity impact may pose a threat to the safety of potato seed. However, even under the condition of $v_1=0.8$ m/s, this study did not find that potato seeds were damaged or injured obviously for this kind of velocity impact, which affected the emergence rate.

Then, in fact, long before this project started, a large number of experiments conducted on a simple potato seed metering test-bed have shown that the increase of empty spoon rate (α_2 , see Part 5) always 0.1%-0.22%, compared with its typical base value 5%, this kind of increase can almost be ignored due to the sudden seed-metering chain (or spoons) speed change within 2-3 times, and this is also the premise that the Catching-up Compensation scheme can be adopted in this study.

Finally, let's see the stability of the compensation control system. In normal operation, the combined mass of motor and one-way clutch only accounts for about 1/15 of the total seeder, and the one-way clutch is switched smoothly, these will reduce the vibration induced by the power shift. However, the sum of acceleration and deceleration time of compensation has a greater impact on mechanical vibration. It is found that, if the scheme below is adopted,

$$(\Delta t_a + \Delta t_d) / t_1 \leq 1 / 20 \tag{19}$$

The vibration of potato seeder is obvious. Therefore, the relationship between Δt_a , Δt_d and t_1 is finally set as

$$(\Delta t_a + \Delta t_d) / t_1 = 1 / 5 \tag{20}$$

Under this parameter and during each compensation, the mechanical vibration caused by the power switching is slight, the measured maximum vibration amplitude of the planter body not more than 0.2 mm, and the frequency is not higher than 7 Hz. So, the system has excellent vibration characteristics.

5 System working performance test

According to this paper, a prototype system is built in Agricultural Engineering Training Center of Gansu Agricultural University as shown by Figure 6a and connected to a tractor when used in field testing shown in Figure 6b.

The whole test is divided into two parts: factory tests and field tests. The factory tests were conducted in dusty environments,

simulating field operations. The tests showed that, the on-board battery (6-QW-36(325)) and electrical motor (86HSE12N) for miss-seeding compensation is sufficient for operation, both the accuracy of miss-seeding detection and the availability detection of potato seeds to be supplemented are not less than 99.9%, which lending credence to the effectiveness of the detection system.

Then, the field tests were conducted shown in Figure 6b, and Figure 6c shows the replanted potatoes, with compensated seeds highlighted in blue, to assess the effectiveness of seed compensation control mechanism described above. Two primary tests were conducted to assess the field performance of the prototype system. The first is to acquire data to determine the relationship between the seed-metering chain speed and the average natural miss-seeding rate. The second quantifies overall performance of the system. The former requires temporary closure of the compensation function and the latter tests system performance with all the functions implemented.

Several parameters were defined for the testing.

The natural empty spoon rate, ζ , is defined as the ratio of natural miss-seeding sowing N_2 to natural sowing N_1 during 3 min operation at a given seed-metering chain speed. Therefore, the average natural miss-seeding rate α_1 can be defined as the arithmetic mean of ζ for the past three tests at the same speed.

When the compensation function is closed, the term “natural empty spoon rate” is used to signify the detection of missing seeds in seed spoon. However, during the second field tests, the

seed-metering chain is accelerated when miss-seeding appears, which in turn may lead to more empty seed spoons as it travels faster through the potato seed tank. The second kind of field tests quantifies the overall system performance by defining a parameter, α_2 , namely the “system full-function average empty spoon rate” over the range of metering chain speeds tested. Similar to ζ , a parameter θ is defined for the “system full-function empty spoon rate,” i.e., the ratio between N_2 to N_1 during the 3 minutes operation at a given seed-metering chain speed. Based upon which, α_2 is calculated by average.

A success criterion of miss-seeding compensation is defined as the deviation of the compensated potato seed from its planned position is less than 50% of L , the distance between adjacent sowed potatoes as planned. “Success compensation rate” parameter, μ , is defined accordingly for system full function performance. Similar α_1 and α_2 , an “average success compensation rate” number, α_3 , is defined. In the beginning, it is noted that the number of “success compensation for miss-seeding” is always less than the compensated sowing, N_3 , for the same period of time. However, after step-by-step parameter adjustment, in the end, all the data N_3 obtained in the tests belong to ‘successful compensation’. In addition, the final effect of compensation can be reflected by “long-term system miss-seeding rate,” α_4 , and it is defined by dividing final missed sowing number, $\sum N_4$, by natural sowing number, $\sum N_1$, for a given seed-metering chain speed for the past 3 tests.



1. Main power transmission one-way clutch 2. Land wheel power transmission chain 3. System controller 4. Vehicle battery 5. Electric motor driver 6. Seed spoon position sensor I 7. Photoelectric sensor set for seed-metering detection I 8. Seed spoon position sensor II 9. Photoelectric sensor set for seed-metering detection II 10. Seed-metering groove.

Figure 6 Prototype model and its field working performance test

The seed-metering chain speed is set to the range of 0.2 to 0.8 m/s. This speed is based on the seed-metering chain speed of 0.3 to 0.7 m/s for planter speeds in field operations in Northwest China. Five seed-metering chain speeds were tested, 0.2 m/s, 0.4 m/s, 0.5 m/s, 0.7 m/s and 0.8 m/s. The test results are summarized in Table 1. The natural empty spoon rate, ζ , and the system full-function empty spoon rate, θ , are below 4% of all tests conducted. The results show that, both α_1 and α_2 increase slightly

with the rise of seed-metering chain speed, v_1 . The data also show that, α_2 is slightly higher than α_1 . The higher system empty spoon can be expected as the Catching-up Compensation mechanism that accelerates the seed-metering chain speed results in a higher uncertainty in capturing the potato seeds. The maximum difference between α_1 and α_2 is only 0.22 percentage points for the tests reported in Table 1, and this proving the rationality of Catching-up Compensation usage in this study from another aspect.

The overall system performance can also be seen from the field test results of α_3 and α_4 . The long-term system miss-seeding rate (α_4) is below 1% for all seed-metering chain speeds tested, except for $v_1=0.8$ m/s, $\alpha_4=1.27\%$. The results of α_1 , α_2 and α_4 demonstrated that, the detection and compensation scheme presented in this paper is effective and reliable when the system is operated in dusty field-testing environments. The data of average success compensation rate, α_3 , decreases with the increasing v_1 .

Over the seed-metering chain speed in the range 0.2 and 0.8 m/s, α_3 decreases from 93.3% to 66.7%, especially, when v_1 is increased from 0.7 to 0.8 m/s, α_3 decreases from 73.30% to 66.70%, and α_4 increases from 0.88% to 1.27%. Although α_3 reduces sharply when v_1 strides across from 0.7 to 0.8 m/s, the value of α_3 is still close to 70%. It's enough to prove that the vast majority of missed sowing can be compensated successfully, this in itself is encouraging.

Table 1 Test data of different speed of Seed-metering chain

Batch	$v_1/\text{m s}^{-1}$	N_1	N_2	N_3	N_4	$\zeta/\%$	$\alpha_1/\%$	$\theta/\%$	$\alpha_2/\%$	$\mu/\%$	$\alpha_3/\%$	$\alpha_4/\%$
1	0.2	792	30	24	6	3.53		3.79		80.00		
2		786	24	24	0	2.98	3.34	3.05	3.52	100.00	93.33	0.25
3		804	30	30	0	3.50		3.73		100.00		
4	0.4	1080	36	30	6	3.16		3.33		83.33		
5		1098	42	36	6	3.65	3.46	3.83	3.68	85.71	84.92	0.55
6		1086	42	36	6	3.57		3.87		85.71		
7	0.5	1224	42	30	12	3.34		3.43		71.43		
8		1235	48	36	12	3.75	3.55	3.89	3.59	75.00	82.14	0.65
9		1220	42	42	0	3.56		3.44		100.00		
10	0.7	1512	54	42	12	3.50		3.57		77.78		
11		1536	60	42	18	3.76	3.60	3.91	3.67	70.00	76.30	0.88
12		1500	53	43	10	3.54		3.53		81.13		
13	0.8	1674	60	42	18	3.51		3.58		70.00		
14		1656	64	36	28	3.67	3.64	3.86	3.80	56.25	66.70	1.27
15		1638	65	48	17	3.74		3.97		73.85		

6 Conclusions

Due to the complex spatial structure of the existing miss-seeding compensation system, and the difficulty in landing point control of the compensated potato seeds, a new kind of integrated seeding and compensating potato planter based on one-way clutch is put forward in this paper. The structure and the system controller of the new potato planter are introduced in the beginning. The key point of this part, how the mechanical system with one-way clutch as its core matches with the detection system, and how it identifies miss-seeding and carries out the needed compensation are revealed in detail. Thus, two important questions, why the new machine has no special channel for miss-seeding compensation and why the structure of the proposed seeder is greatly simplified are answered.

Of course, the miss-seeding compensation control rules and its related kinematics are the most important theoretical basis of this paper. In this part, not only how Catching-up Compensation theory is implemented is elaborated in detail, but also the specific control basis and implementation means are given completely. In addition, potato seed and system stability analysis are studied quantitatively and qualitatively respectively, and its conclusion is also the theoretical premise of the Catching-up Compensation scheme.

The results of field tests show that, the design of the integrated seeding and compensating potato planter based on one-way clutch is workable. The main power and compensation power can transfer logically and rapidly. Although the average success compensation rate decreases evidently with the increase of the seed-metering chain speed, the success compensation rate is not less than 80% at 0.5 m/s or below, and it is still close to 70% even at a higher seeding speed, such as 0.8 m/s. Therefore, the new concept potato planter described in this paper is basically successful, and has significant commercial application value.

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Nomenclature

Term	Meaning	Unit
L_1	Distance between the adjacent seed spoon position sensors	m
r	Average radius of the cutting potato seeds	cm
N_1	Natural sowing number	
N_2	Natural miss-seeding sowing number	
N_3	Compensated sowing number	
N_4	Final missed sowing number	
v_1	Real-time speed of seed-metering chain	m s^{-1}
v'_1	Compensating speed of seed-metering chain	m s^{-1}
L	Distance between the adjacent sowed potatoes	m
ω_1	Real-time angular speed of the seed-metering chain wheel	rad s^{-1}
n_1	Number of teeth of the electric motor power output chain wheel	
n_2	Number of external teeth of the compensating one-way clutch	
ω'	Angular speed of the electric motor under compensation	rad s^{-1}
t_1	Run time of the electrical motor for compensation	s
K_1	Motion compensation coefficient during miss-seeding compensation	
ζ	Natural empty spoon rate (N_2/N_1 in each specific first kind of test with closure of the compensating function, different v_1 , different ζ)	%
α_1	Average natural miss-seeding rate (the arithmetic mean of ζ)	%

Term	Meaning	Unit
θ	System full-function empty spoon rate (N_2/N_1 in each specific second kind of test with all the functions implemented, different v_1 , different θ)	%
α_2	System full-function average empty spoon rate (the arithmetic mean of θ)	%
μ	Success compensation rate (N_3/N_1 in each specific second kind of test, different v_1 , different μ)	%
α_3	Average success compensation rate (the arithmetic mean of μ)	%
α_4	Long-term system miss-seeding rate ($\sum N_4/\sum N_1$ for each given v_1 for the past 3 tests)	%

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