Optimized design and performance evaluation of an electric cup-chain potato metering device

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Abstract: The cup-chain metering device is commonly used in potato planters despite its problems of missing-seeding, double-seeding and ground wheel sliding. A mechanical-electrical design was developed for planters to resolve these problems. A regression experiment was conducted with three factors (chain speed, chain tightening distance and cup tilting) and two indicators (missing-seeding rate and double-seeding rate). Based on the results of regression experiment, a numerical regression model was built and a multi-objective optimization method was used to get an optimal solution. Subsequently, the optimized device was tested in the field. The device design presents a tilting seed cup with a guard plate and an electric control system. The laboratory test showed that the missing-seeding rate increased with the chain speed. It initially decreases and then increases with the chain tightening distance and cup tilting angle. The double-seeding rate declines with chain speed. It increases initially and declines afterward with the chain tightening distance. The optimization resulted in a missing-seeding rate of 4.39% and a double-seeding rate of 8.78% under the parameters of 0.32 m/s seeding speed, 0.94×10^{-3} m tightening distance, and 12.5° cup tilting angle. The field test demonstrated that electric control instead of ground wheel-driven chain enables fast seeding and precise intra-row seeding distance.

Keywords: potato planter, cup-chain metering device, multi-objective optimization, regression method

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1 Introduction

Potato is the fourth largest staple crop in China. The potato planting area and production of China have ranked first in the world in recent years\cite{1}. In 2013, the planting area in China was 6.7 million hectares. The mechanical sowing rate was 23\%\cite{2}. Currently, the common metering devices used in potato planters include cup-chain, air suction and belt conveyor\cite{3-6}. Air suction metering devices work with high negative pressure and are only applicable for large power tractors. Belt conveyors have already been applied because of their high efficiency and less missing-seeding (a seed cup failed filled seed) and double-seeding (a seed cup filled with two seeds). However, the low metering spacing precision of belt conveyors as influenced by seed size needs to be improved\cite{7,8}. Cup metering is the most widely used metering device because of its high reliability, low cost and adjustable plant spacing. It can be utilized in intra-row and line spacing. However, cup metering still has the problem of missing-seeding (MS), double-seeding (DS), and ground wheel sliding\cite{9,10}.

Capacity and accuracy of plant spacing are the main indicators of machine performance. High accuracy of plant spacing results in high yield and a uniform sorting of the tubers at harvest. Field measurements of planting distance in the Netherlands revealed a coefficient of...
variation of around 20%. Earlier studies in Canada and the USA showed even higher coefficient of variations up to 69% \cite{8,11-13}.

Based on the drive type, cup style can be divided into cup-chain and cup-belt. Cup-belt is often utilized in large tractors because of its strong demand for power, as demonstrated by the highly reliable German Grimme GL series potato planter that combines mechanical, electrical, hydraulic, and controller features with high reliability \cite{14,15}. Cup-chain is utilized in small and medium tractors with low power demands. Influenced by polygonal action, the cup-chain metering device has a vibration effect and has higher missing-seeding rate (MSR) and lower double-seeding rate (DSR) than cup-belt metering device \cite{16,17}. Artificial assistance metering can resolve these problems effectively but with increased labor intensity and potential safety problems \cite{18-20}. Hongzhu Nongji Co. Ltd. (China) designed a motor vibration device to reduce the double-seeding rate of metering devices and improve metering performance. Lu designed a mechanical vibration device to reduce the double-seeding rate \cite{21}. PARMA Company designed a stirring cam to solve the seed blocking problem \cite{22}. Cup size has a significant effect on metering performance. Cup size is generally 1.2 to 1.6 times of the potato size. Hongzhu Nongji Co. Ltd. (China) designed a combination cup to improve device adaptability to different seed sizes. Han Heng conducted research on the belt-cup potato metering device \cite{23}. In this study, the influence of belt tension, planter working speed, position of the vibration wheel, and seed filling height on misses and multiples indexes was revealed through experiments.

In the current research, a cup-chain potato metering device equipped tilting cups with guard plates are designed and constructed. The difference between the actual center distance and theoretic center distance is defined as chain tightening distance (CTD). This device was laboratory tested with three factors, namely, chain speed (CS), CTD, and cup tilting angle (CTA), and three indicators, namely, MSR, DSR and spacing. A regression experiment was conducted with three factors (CS, CTD and CTA) and two indicators (MSR and DSR). Based on the regression experiment result, a numerical regression model is built and a multi-objective optimization method is used to get an optimal solution. Subsequently, the optimized device was tested in the field. The device designed presents a tilting seed cup with a guard plate and an electric control system. A control system for metering was developed to resolve the slipping of the ground wheel. The metering chain is driven by a motor, and the driving speed is determined by tractor speed, which is achieved by differential GPS.

2 System design

2.1 Working principle and analysis of factors

The cup-chain potato metering device is shown in Figure 1. The cup-chain device goes through the potato pile and isolates one potato from the others for single grain metering. The metering direction is marked as $v$ in Figure 1. Metering success rate is determined by the number of potato seeds in region C and is influenced by the potato flow behavior and metering speed. Furthermore, the potato can be dropped from the cup because of equipment bumps and chain shaking.

![Figure 1 Schematic of the cup-chain potato metering device](image)

Point A in Figure 1 shows that the cup tilting angle is defined as the angle between the cup-chain and the normal line of the fixed point. Generally, the cup is placed perpendicular to the chain, with a CTA of 0°. In this condition, the forces acting on the potato in the cup include gravity and the supporting force from the cup. With equipment bumping and chain shaking, the potato
can be dropped from the cup.

Figure 2 shows the forces acting on the potato in the tilted cup. The forces acting on the potato include gravity $G$, supporting force $P$ from the cup, and supporting force $N$ from the guard plate. While the potato tends to separate from the cup under the conditions of device bumping and chain shaking, the guard plate acts as friction force $f$ on the potato which prevents the shedding phenomenon occurs. Friction force increases and the shaking phenomenon decreases with the increase in CTA. Meanwhile, the effective area that contributes to metering decreases, which leads to an increase in MSR.

Figure 2 Stress analysis of a potato

The metering chain should neither be too tight nor too loose. A metering chain that is too tight causes a polygonal action, with the results of MSR increase and DSR decrease. A metering chain that is too loose easily causes chain shaking and collision with other components, with the results of MSR increase and DSR decrease.

On the basis of predecessor findings and above analysis, studied factors in this paper are CS, chain tightening tension, and CTA. Chain tightening tension is evaluated by CTD.

Ground wheel slipping is mainly the result of lacking driving capacity, which can be caused by huge load torque or ground drive failed attached to the soil/residue surface. To solve this problem, a motor was employed to drive the metering device instead of the ground wheel. Working speed was measured by differential GPS. A metering control system was developed to control the metering speed according to the ground wheel speed.

2.2 Mechanical system design

The mechanical system is an improvement of the potato planter type 1220 produced by Menoble Company. The structure is shown in Figure 3.

![Figure 3 Structure of the metering test device](image)

2.3 Control system design

The metering control system consists of a microcontroller, a motor control circuit, and a GPS communication circuit. The microcontroller is a microcomputer PIC18F2580 produced by Microchip Company. The control signal was amplified by a D/A translate box through an electrical signal control servo motor to adjust the metering speed. Working speed was measured by the differential GPS and achieved through the RS232 serial port. The main controller implements closed loop control using the PID control algorithm for the feedback signal. Figure 4 shows a block diagram of the control system principle.
2.4 Tests

2.4.1 Test apparatus

Type PS70 precision planetary gear box (Newstart Gear Transmission Co., Ltd.), type SGMJV-04ADE6S servo motor (Yaskawa Electric Corporation), type SGDV-2R8A01B002000 servo driver (Yaskawa Electric Corporation), and analysis software DPS v7.05 and Matlab R2012A were utilized.

2.4.2 Test materials

The future development trend of potato seeds will utilize entire potatoes rather than diced potatoes \(^{[24]}\). In this test, the seed material was naturally matured and harvested manually. The species is Holland 15, cultivated by Zhangjiakou Academy of Agricultural Sciences. According to user guide of type 1220 potato planter, the mean diameter of potato seed selection is 56 mm.

2.4.3 Test method

A laboratory test was conducted according to the standard GB/T 6242-2006 Equipment for Planting-Potato Planters-Method of Testing \(^{[25-29]}\). On the basis of test scheme, each parameter was set. Then, the seed box was filled with the potato seeds.

By mounting two laser sensors on seed discharge hole, the number of missing-seeding can be calculated with logic output. The number of double seeding can be observed. Then, MSR and DSR can be calculated. With the furrow coverer of potato planter removed, the plant spacing can be measured easily.

3 Test results and analysis

3.1 Test model

Test conducted with quadratic general rotary unitized design regression testing method. Multi-objective optimization method is used to get an optimal solution \(^{[24]}\). According to the related technical standard and preliminary test results, the value of each factor and range were determined.

The best level of value was encoded as space factor 0 according to the factor value range. Each factor code was determined.

In the test index, \(y_1\) is MSR and \(y_2\) is DSR. Experimental factors \(x_1\), \(x_2\), and \(x_3\) are the encoded values of \(CS_v\), \(CTD_d\), and \(CTA_\alpha\). The coding of the regression test is shown in Table 1. The design and results are shown in Table 2.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Test factors</th>
<th>Test indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 1 1</td>
<td>7 11.3</td>
</tr>
<tr>
<td>2</td>
<td>1 1 –1</td>
<td>6 10.9</td>
</tr>
<tr>
<td>3</td>
<td>1 –1 1</td>
<td>6.2 6.7</td>
</tr>
<tr>
<td>4</td>
<td>1 –1 –1</td>
<td>5.8 6.7</td>
</tr>
<tr>
<td>5</td>
<td>–1 1 1</td>
<td>4.9 13.5</td>
</tr>
<tr>
<td>6</td>
<td>–1 –1 1</td>
<td>4.7 12.4</td>
</tr>
<tr>
<td>7</td>
<td>–1 –1 –1</td>
<td>4.6 8.5</td>
</tr>
<tr>
<td>8</td>
<td>–1 0 0</td>
<td>5 7.9</td>
</tr>
<tr>
<td>9</td>
<td>–1.682 0 0</td>
<td>3.6 11.3</td>
</tr>
<tr>
<td>10</td>
<td>1.682 0 0</td>
<td>6.1 8.5</td>
</tr>
<tr>
<td>11</td>
<td>0 –1.682 0</td>
<td>6.5 5.8</td>
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<td>14</td>
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<tr>
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<td>0 0 0</td>
<td>4.1 10.6</td>
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<td>16</td>
<td>0 0 0</td>
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<tr>
<td>17</td>
<td>0 0 0</td>
<td>4.3 10.6</td>
</tr>
<tr>
<td>18</td>
<td>0 0 0</td>
<td>4.2 10.5</td>
</tr>
<tr>
<td>19</td>
<td>0 0 0</td>
<td>4.1 10.4</td>
</tr>
<tr>
<td>20</td>
<td>0 0 0</td>
<td>4.2 10.4</td>
</tr>
</tbody>
</table>

The regression equation of MSR is:

\[
y_1 = 4.1662 + 0.7326x_1 + 0.1102x_2 + 0.1371x_3 + 0.2447x_4 + 0.8811x_5 + 0.2271x_6 + 0.125x_7 + 0.2x_8 + 0.15x_9 + 0.03x_{10}
\] (1)
\[ y_2 = 10.5333 - 0.8354x_1 + 2.2882x_2 + 0.2523x_3 - 0.224x_1^2 - 0.3124x_2^2 - 0.2593x_3^2 \]  
(2)

The \( F \)-tests of regression Equations (1) and (2) are shown in Table 3. The comparison of the calculated result with \( F_{0.01}(9,10)=4.94 \) shows that both of the regression equations are remarkable. The regression model can reflect actual situations well.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Source</th>
<th>Sum of squares</th>
<th>Degree of freedom</th>
<th>F-value</th>
<th>Significance</th>
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</thead>
<tbody>
<tr>
<td>MSR</td>
<td>Regression</td>
<td>20.1554</td>
<td>9</td>
<td>2.2395</td>
<td>525.83</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>0.0426</td>
<td>10</td>
<td>0.0043</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>20.1980</td>
<td>19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSR</td>
<td>Regression</td>
<td>84.8813</td>
<td>9</td>
<td>9.4313</td>
<td>1229.74</td>
</tr>
<tr>
<td></td>
<td>Residual</td>
<td>0.0767</td>
<td>10</td>
<td>0.0077</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum</td>
<td>84.9580</td>
<td>19</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ R^2=0.9150 \quad S=0.141 \quad \alpha=0.00 \]

3.2 Factor effect analysis

3.2.1 Main effect analysis

The partial regression coefficients were standardized because the factors were substituted by dimensionless linear. Two factors were fixed on level 0, so the third factor influences were determined.

\[ y_1(x_1) = 4.1662 + 0.7326x_1 + 0.2447x_1^2 \]  
(3)
\[ y_1(x_2) = 4.1662 + 0.1102x_2 + 0.8811x_2^2 \]  
(4)
\[ y_1(x_3) = 4.1662 + 0.1371x_3 + 0.2271x_3^2 \]  
(5)
\[ y_2(x_1) = 10.5333 - 0.8354x_1 - 0.224x_1^2 \]  
(6)
\[ y_2(x_2) = 10.5333 + 2.2882x_2 - 0.3124x_2^2 \]  
(7)
\[ y_2(x_3) = 10.5333 + 2.2523x_3 - 0.2593x_3^2 \]  
(8)

The main effects between each factor and MSR and DSR are shown in Figures 5 and 6. MSR increases with CS; it initially decreases and then increases with CTD and CTA. DSR declines with CS; it increases initially and then decreases afterward with CTD. With CTA, it initially decreases and then increases. CS and CTD have a greater influence on MSR and DSR than CTA.

The test results show that the chances that the potato will fall to the cup decreases with the increase in CS, thus, MSR increases and DSR decreases.

The chain easily slackens and swings during vertical lifting with the decrease in CTD. MSR increases because a potato can easily fall from the cup. The chain free swinging phenomenon disappears, MSR decreases, and DSR increases with the increase in CTD. As CTR increases, the polygonal action becomes significant, chain shaking intensifies, MSR increases, and DSR decreases.

The chances that a potato will fall from the cup can be improved by increasing CTA appropriately. The MSR rate increases with the increase in CTA. Thus, with the increase in CTA, MSR decreases initially and then increases, which is contrary to DSR.

3.2.2 Response surface analysis

When one factor is fixed at level 0, the binary quadratic equation of the other two factors is determined. The interaction equations of MSR and DSR are presented by Equations (1) and (2). The interactive effect of the factors and contour on MSR and DSR are shown in Figures 7 and 8.

Figure 7 shows the interactive influence of factors on MSR is significant. The interactive influence sequence is as follows: CS and CTD, CS and CTA, CTD and CTA. MSR is less than 10% when CS is less than 0.46 m/s, CTD is in the range of \(0.81 \times 10^{-3}\) m to \(3.19 \times 10^{-3}\) m, and CTA is in the range of 8° to 16°.
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The national standards for potato planter performance indicators are as follows: MSR of less than 10% and DSR of less than 20%. For DSR and MSR, smaller is better. Based on the above model, the mathematical model for determination is as follows:

\[
\min F(X_j) = y_1 \\
\min F(X_j) = y_2 \\
X_j \in [-1.682, 1.682]
\]

The model is a multi-objective optimization problem. Sequential quadratic programming method is utilized to solve this problem. The method is accomplished by the “fgoalattain” function of the MATLAB optimization toolbox. By using coded formula back substitution to optimize the variables, the actual values of each optimized factor were determined as follows: CS is 0.32 m/s, CTD is 0.94×10^{-3} m, CTA is 12.5°, MSR is 4.39%, and DSR is 8.78%.

To verify the reliability of the optimized results, a test was conducted. The results are shown in Table 4. The authentication and predicted values are similar. The test results show that the regression model is reliable and can be used to predict and analyze the potato metering device.

### Table 4  Experimental scheme and results for prediction verification

<table>
<thead>
<tr>
<th>Number</th>
<th>Test scheme</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS v/m·s⁻¹</td>
<td>CTD d/10⁻³ m</td>
<td>CTA α/(°)</td>
</tr>
<tr>
<td>1</td>
<td>0.32</td>
<td>0.94</td>
</tr>
<tr>
<td>2</td>
<td>0.32</td>
<td>0.94</td>
</tr>
<tr>
<td>3</td>
<td>0.32</td>
<td>0.94</td>
</tr>
</tbody>
</table>

### 3.4 Field test

The field test scheme and results are shown in Table 5. Type I is type 1220 potato planter designed by Menoble Corporation. Type II is the planter with optimization parameters.

Field test was conducted on October 18, 2015 in Chinese Academy of Agricultural Mechanization. Field flatness and crop stubble have influenced on sowing precision of potato planter. Major agricultural production process for reference, land preparation was conducted including subsoiling and rotary tilting operation.
Table 5  Field experimental scheme and results

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>MSR, %</th>
<th>DSR, %</th>
<th>Spacing, y/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I</td>
<td>8.6</td>
<td>9.3</td>
<td>319</td>
</tr>
<tr>
<td>2</td>
<td>I</td>
<td>7.7</td>
<td>8.5</td>
<td>307</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>8.2</td>
<td>8.4</td>
<td>312</td>
</tr>
<tr>
<td>4</td>
<td>II</td>
<td>4.9</td>
<td>8.1</td>
<td>281</td>
</tr>
<tr>
<td>5</td>
<td>II</td>
<td>5.1</td>
<td>7.8</td>
<td>281</td>
</tr>
<tr>
<td>6</td>
<td>II</td>
<td>5.2</td>
<td>7.6</td>
<td>282</td>
</tr>
</tbody>
</table>

The test results show that the MSR of type II decreases from 8.2% to 5.1% and DSR drops from 8.7% to 7.8% compared with those of type I. The average intra-row space is $281.3 \times 10^{-3}$ m, which is better than that of type I ($312.7 \times 10^{-3}$ m).

4 Conclusions

1. Within the scope of the test, the MSR increases with the CS; it initially decreases and then increases with the CTD and CTA. The DSR declines with the CS, increases initially, and decreases afterward with the CTD; meanwhile, it initially decreases and then increases with the CTA.

2. MSR and DSR are both influenced by CS significantly, which determines the filling time. Chain tightening extent is decided by CTD, which is important to chain shaking and polygonal action. CTA has a large influence on the stability of the potato in the cup.

3. The optimization results show a MSR of 4.39% and a DSR of 8.78% under the parameters of 0.32 m/s seeding speed, 0.94×10⁻³ m tightening distance, and 12.5° cup tilting angle.

4. The field test indicates that electric control instead of ground wheel-driven chain enables the increase in seeding speed and precision in intra-row seeding distance.

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[References]


