

Design and Modeling Analysis of a Seed Metering Mechanism for a Small Electric Intelligent Seeding Vehicle

Pengda An, Yaqing Guo, Weihang Wang, Lingling Li*

University of Science and Technology Liaoning, Anshan, Liaoning, 114051 China

ABSTRACT

Aiming at the problems of large equipment size and poor trafficability in small plots and facility agriculture, a small electric intelligent seeding vehicle was designed, with a focus on the structural design, parametric modeling and simulation analysis of its core component—the seed metering mechanism. An inclined disc metering principle was adopted. A multi-constraint optimization algorithm for determining the cell dimensions was proposed based on seed geometric characteristics, and an adaptive control algorithm matching the metering disc rotational speed with the vehicle speed was established. A three-dimensional solid model of the seed metering mechanism was built using SolidWorks. Finite element static and modal analyses were performed using ANSYS Workbench, and multi-body dynamics simulation was carried out with ADAMS to obtain the seeding performance indices at different rotational speeds. Simulation results showed that the maximum stress of the metering disc was 18.5 MPa, far below the material yield strength, and the highest seed spacing quality index reached 93.2%, verifying the rationality of the structural design and the feasibility of field operation. This research provides a theoretical basis and data support for the development of small electric intelligent seeding equipment.

KEYWORDS

Small seeder; Electric intelligent vehicle; Seed Metering mechanism; Cell design; Finite element analysis; Motion simulation

1 Introduction

With the rapid development of smart agriculture and facility horticulture, there is an increasingly urgent demand for miniaturized, lightweight, and electric intelligent seeding equipment suitable for small plots, greenhouses and hilly mountainous areas. Traditional seeders are mostly powered by large- and medium-sized internal combustion engines, which have bulky structures, are difficult to operate flexibly in narrow spaces, and have prominent emission problems. Small electric intelligent seeding vehicles, with advantages such as zero emissions, low noise and easy manipulation, are becoming one of the hotspots in precision agriculture technology research. As the core working component of the seeding vehicle, the seed metering mechanism directly determines the seeding accuracy, plant spacing uniformity and seedling emergence quality, and is the top priority in the design of the whole machine. Currently, scholars at home and abroad have conducted extensive research on precision seed meters. Mechanical seed meters mainly include the fluted roller type, the inclined disc type, and the finger pick-up type, among which the inclined disc seed meter is widely used because of its simple structure, good adaptability to seeds and strong seed filling ability. However, the cell parameter design mostly relies on empirical trial-and-error, and there is a lack of quantitative design algorithms associated with the physical dimensions of seeds. Moreover, research on the coordinated control of seed metering and vehicle speed for small electric platforms is relatively scarce. For this reason, this paper designs an inclined disc seed metering mechanism suitable for a small electric intelligent seeding vehicle, proposes a cell parameter optimization algorithm based on the triaxial dimensions of seeds, establishes a complete three-dimensional model and conducts finite element analysis and multi-body dynamics simulation, and simultaneously develops a vehicle speed adaptive seeding control algorithm, with the aim of improving the digital design level and working quality of the seed metering mechanism.

2 Overall Scheme of the Small Electric Intelligent Seeding Vehicle

2.1 Overall Structure and Working Principle

The small electric intelligent seeding vehicle is mainly composed of a frame, a traveling system, an electronic control system, a seeding unit and a sensor module, as shown in Figure 1. The frame is assembled from aluminum alloy profiles, supported by four wheels, with the two rear wheels independently driven and the front wheels being caster wheels. The traveling motor is a 200 W brushless DC motor that drives the rear wheels through a chain transmission, and the speed can be continuously adjusted in the range of 0.2–0.8 m/s. The seeding unit is fixed at the rear of the frame, including a seed hopper, a seed meter, a furrow opener, a covering wheel and a press wheel. The seed meter is independently driven by a 57-series stepper motor, which can adjust the rotational speed in real time according to the vehicle speed signal, thus achieving consistent plant spacing. The control system adopts an STM32F407 as the core, integrated with a Hall vehicle speed sensor, a laser ranging obstacle avoidance module and a wireless remote control module, possessing both autonomous navigation and remote control modes.

* **Corresponding Author:** Lingling Li, lilingling1965@126.com

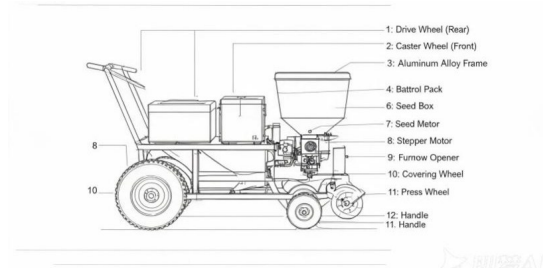


Figure 1 Structural sketch of the small electric intelligent seeding vehicle

2.2 Main Technical Parameters

Considering the agronomic requirements of vegetables and legume crops, the main technical parameters of the vehicle and the seed metering mechanism were determined, as shown in Table 1.

Table 1 Main technical parameters of the small electric intelligent seeding vehicle

Parameter	Value
Overall dimensions (L×W×H) /mm	1200×550×680
Total mass /kg	35
Power source	24 V 20 Ah lithium battery
Traveling motor power /W	200
Number of rows	1
Seeding depth /mm	15–50 (adjustable)
Plant spacing /mm	150–300 (settable)
Seed meter type	Inclined disc
Metering disc diameter /mm	160
Number of cells	24
Applicable seeds	Soybean, pea, maize, etc.

3 Design of the Seed Metering Mechanism

3.1 Selection and Working Principle of the Seed Meter

Comparing the external grooved wheel type, the cell wheel type and the pneumatic type seed meters, the small electric platform is limited by power and space and is not suitable for methods that require a fan or complicated transmission. The inclined disc seed meter uses gravity and centrifugal force synergistically to fill seeds, requires no air source, has low power consumption, and is highly adaptable to seed shapes; therefore, it was chosen as the metering element for this vehicle. Its working principle is shown in Figure 2: seeds in the hopper fall under gravity onto the upper part of a rotating metering disc installed at an inclination of 45° to the horizontal. A number of cells are evenly distributed along the circumference of the disc. When the cells pass through the seed pile, they capture one or two seeds; as the disc rotates, the cells leave the seed layer and enter the clearing zone, where an elastic brush wheel scrapes off excess seeds; when the cell rotates to the seed discharge opening at the bottom of the housing, the seed leaves the cell under the action of gravity and centrifugal force and falls into the furrow formed by the opener, thus completing single-seed precision planting.

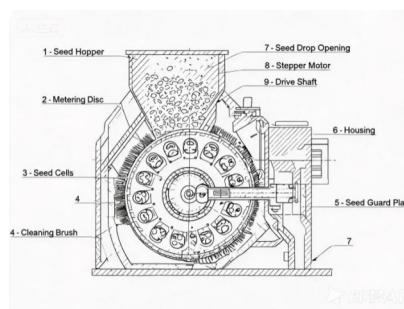


Figure 2 Assembly diagram of the seed metering mechanism

3.2 Key Parameter Design of the Metering disc

3.2.1 Disc Diameter and Number of Cells

Let the planting spacing be S (m), the vehicle working speed be v (m/s), and the number of cells on the metering disc be Z ; then the disc rotational speed n (r/min) must satisfy:

$$n = \frac{60v}{ZS}$$

Taking a typical working condition $v = 0.5$ m/s, $S = 0.2$ m and $Z = 24$, the calculated $n = 6.25$ r/min. To accommodate

higher speed operations and different plant spacings, the working rotational speed range of the metering disc was set to 5–30 r/min. Considering both the seed filling performance and a compact structure, the outer diameter of the metering disc D_p was set to 160 mm, and the cell distribution circle diameter d_m to 130 mm. The arc length spacing between cells is approximately 17 mm, which can effectively prevent the seed cluster from bridging.

3.2.2 Cell Shape and Size Design

The geometric parameters of the cell are key factors affecting the seed filling, clearing and discharging performance. Taking soybean (variety: Zhonghuang 13) as the working target, the measured average seed dimensions are: length $L = 7.5$ mm, width $W = 6.5$ mm, thickness $T = 5.5$ mm, and sphericity approximately 0.85. The cell was designed as a conical-cylindrical composite cavity, with the upper conical part guiding the seed to slide in and the lower cylindrical part accommodating a single seed. The cell diameter D must allow seeds of various sizes to enter smoothly but must not accommodate two seeds simultaneously, and can be determined based on the seed width. The cell depth H should ensure that the seed's center of gravity enters the cell without jamming. Here, a cell parameter determination algorithm based on seed dimensions is proposed (Algorithm 1).

Algorithm 1: Initial cell size determination algorithm

Input: Average seed width W , average thickness T , seed length L , filling angle α (45°)

Output: Cell diameter D , depth H

Steps:

Step 1 Calculate the reference diameter $D_0 = (1.15 \sim 1.35) \times W$, taking the median value $1.25W = 8.125$ mm, rounded to 8.0 mm.

Step 2 Calculate the reference depth $H_0 = (0.55 \sim 0.75) \times T$ to ensure the seed's center of gravity falls into the cell, taking $0.65T \approx 3.58$ mm, rounded to 3.6 mm.

Step 3 Length correction: If the seed length-width ratio $L/W > 2.2$, increase D_0 : $D = D_0 + 0.3(L/W - 2.2)W$; otherwise, $D = D_0$.

Step 4 Self-flow filling condition check: The component of gravity along the disc surface must make the seed slide into the cell, i.e., require the cell cone angle β to satisfy $\tan\beta \geq \mu$, where μ is the friction coefficient between the seed and the disc surface, taken as 0.35. A cone angle of 60° was selected, satisfying the condition.

Step 5 Output $D = 8.0$ mm, $H = 3.6$ mm, total cell depth (including the cone height) 5.8 mm, cone angle 60° , and cylindrical section length 2.8 mm.

The designed cell structure is shown in Figure 3. This cell ensures that seeds within a certain size range can be reliably filled, and redundant seeds can be removed by the clearing brush.

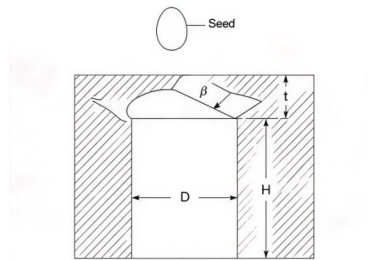


Figure 3 Cell cross-section structure and parameters

3.3 Multi-objective Optimization Algorithm for Cell Parameters

The actual seed dimensions follow a normal distribution. To improve adaptability to bulk seeds, the cell diameter D and depth H were fine-tuned and optimized with the objectives of maximizing the seed filling success rate and minimizing the seed jamming rate. The optimization model is established as follows:

$$\begin{cases} \text{Max} P_s(D, H) = \frac{N_{\text{filled}}}{N_{\text{total}}} \\ \text{Min} P_j(D, H) = \frac{N_{\text{jammed}}}{N_{\text{total}}} \\ \text{s.t. } D \in [1.1W_{\text{max}}, 1.5W_{\text{min}}], H \in [0.5T_{\text{max}}, 0.9T_{\text{min}}] \end{cases}$$

Based on the Monte Carlo stochastic simulation and discrete element ideas, an iterative optimization algorithm was compiled, and its pseudo-code is shown in Algorithm 2.

Algorithm 2: Iterative optimization algorithm for cell parameters

Input: Seed dimension sample set (W_i, T_i) , sample size N , initial values D_0, H_0 , maximum number of iterations M

Output: Optimal $D_{\text{opt}}, H_{\text{opt}}$

(1) Initialize $D = D_0, H = H_0$, best fitness value $f_{\text{best}} = 0$

(2) for $iter = 1$ to M do

(3) For each set of seed dimensions, simulate the filling process: if a seed can enter the cell as a single grain, count as

success; if the seed cannot slide in or gets stuck, count as failure.

(4) Calculate the filling success rate P_s and jamming rate P_j , fitness $f = P_s - 2P_j$

(5) If $f > f_{best}$ then update $D_{opt} = D$, $H_{opt} = H$, $f_{best} = f$

(6) Adjust D and H along the gradient direction with a step size $\Delta D = 0.05$ mm, $\Delta H = 0.05$ mm, and proceed to the next round

(7) end for 8. Return D_{opt}, H_{opt}

After optimization, the final cell diameter was determined as $D = 8.2$ mm, depth $H = 3.8$ mm, with a theoretical filling success rate reaching 96.5% and a jamming rate below 1.8%. The optimization flow is shown in Figure 4.

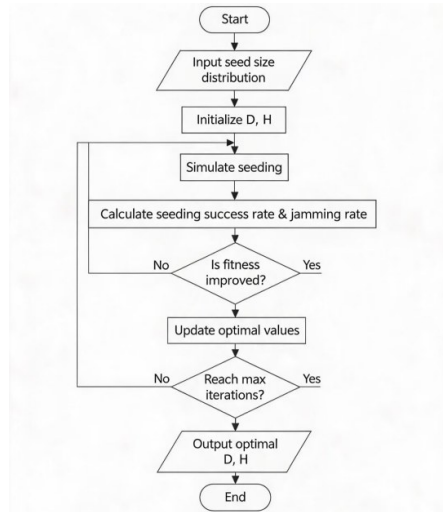


Figure 4 Flowchart of the cell parameter optimization algorithm

3.4 Design of the Seed Clearing and Guarding Devices

The seed clearing device uses an elastic brush wheel arranged 15° above the horizontal position of the metering disc, with a gap of 0.5 mm between the brush and the disc surface, which can effectively remove excess seeds without damaging the seed grains. The guard plate is made of a 0.3 mm stainless steel spring sheet, fitted closely to the inner wall of the housing, extending from the clearing zone to the seed discharge opening, preventing seeds from falling midway. The seed discharge opening is positioned 8° behind the lowest point of the metering disc, allowing the seeds to fall in an approximately vertical direction, thereby reducing the plant spacing variation.

4 3D Modeling and Simulation Analysis of the Seed Metering Mechanism

4.1 3D solid Modeling

Under the SolidWorks 2022 environment, the three-dimensional modeling of the metering disc, housing, seed hopper, brush wheel, guard plate, drive shaft and other components was completed, and the digital prototype of the seed metering mechanism was generated according to the assembly relationship, as shown in Figure 5. Material properties such as aluminum alloy 6061, acrylic glass and nylon were assigned to the parts. Interference checks showed that the minimum clearance between moving parts was 1.2 mm, indicating a reasonable assembly relationship.

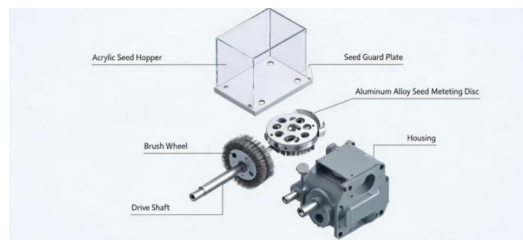


Figure 5 3D exploded view of the seed metering mechanism

4.2 Finite Element Static Analysis

The metering disc model was imported into ANSYS Workbench, meshed with tetrahedral elements of 2 mm element size, generating a total of 46,328 nodes and 23,710 elements. The disc material was aluminum alloy 6061-T6, and its mechanical properties are listed in Table 2. Constraint condition: fixed constraint was applied to the central shaft hole; load condition: centrifugal force caused by the rotational speed and the seed pressure acting on the cells were applied. When the disc rotated at the maximum speed of 30 r/min, the equivalent centrifugal force produced a radial force of about 4.8 N at the cell distribution circle. Considering the seed friction load, the total load was about 6.2 N. The solved

stress distribution is shown in Figure 6.

Table 2 Material properties of the metering disc

Material	Density/(kg·m ⁻³)	Elastic modulus/GPa	Poisson's ratio	Yield strength/MPa
Aluminum alloy 6061-T6	2700	69	0.33	276

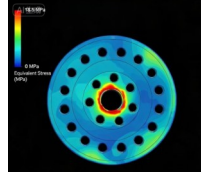


Figure 6 Equivalent stress nephogram of the metering disc

The maximum equivalent stress is 18.5 MPa, far lower than the material yield strength of 276 MPa, giving a safety factor of 14.9, indicating ample structural strength. Modal analysis of the metering disc showed that the first-order natural frequency is 285 Hz, while the frequency corresponding to the maximum working rotational speed is only 0.5 Hz, thus resonance will not occur.

4.3 Multi-body Dynamics Motion Simulation

To verify the seeding performance, the 3D model was imported into ADAMS software, and spherical particles were generated to simulate soybean seeds. The particle radius was based on the equivalent sphere diameter of the triaxial dimensions. Contact parameters between seeds and between seeds and the metering disc were set (coefficient of restitution 0.5, static friction coefficient 0.35, dynamic friction coefficient 0.1). A rotational joint was added to the disc, and the brush clearing contact force and gravity field were applied. The disc rotational speeds were set to 10 r/min, 15 r/min, 20 r/min and 25 r/min, with a simulation time of 10 s. The proportion of cells that successfully delivered a single seed was counted. A screenshot of the seed motion trajectories at a certain moment is shown in Figure 7.



Figure 7 ADAMS motion simulation seed trajectories ($n = 15$ r/min)

The simulation results are listed in Table 3. It can be seen that the qualified index is the highest at 93.2% when the disc speed is 15 r/min, with a miss index of 3.8% and a multiple index of 3.0%. As the rotational speed increases, excessive centrifugal force leads to insufficient filling and increased misses. Taking both efficiency and accuracy into consideration, the recommended working speed range is 15–20 r/min. The corresponding plant spacing adjustment can be achieved by changing the vehicle speed or the number of cells.

Table 3 Simulation results of seeding performance at different rotational speeds

Rotational speed/(r/min)	Qualified index/%	Miss index/%	Multiple index/%
10	91.8	4.5	3.7
15	93.2	3.8	3.0
20	91.5	4.6	3.9
25	87.3	7.9	4.8

5 Design of the Seeding Control Algorithm

To enable the seed metering mechanism to adapt to changes in the vehicle's working speed and to maintain a constant set plant spacing, a real-time vehicle speed feedback adaptive control algorithm for the disc rotational speed was designed. The control system hardware consists of an STM32F407 microcontroller, a Hall vehicle speed sensor, and a stepper motor driver. The speed sensor is installed on a driven wheel, outputting 12 pulses per revolution, from which the actual vehicle speed v is calculated. Based on the user-set plant spacing S and the number of cells Z , the target metering speed is given by the formula $n_{set} = 60v/(Z \cdot S)$. To compensate for the dynamic response and nonlinearity of the stepper motor, an incremental PID controller is introduced. The pseudo-code of the control algorithm is shown in Algorithm 3, and the flow is illustrated in Figure 8.

Algorithm 3: Adaptive control of the metering disc rotational speed

Input: Set plant spacing S_{set} , number of cells Z , current vehicle speed $v(k)$

Output: Stepper motor pulse frequency f

- (1) Calculate target rotational speed $n_{target} = 60 \cdot v(k) / (Z \cdot S_{set})$
- (2) Read the current actual rotational speed n_{actual} from the encoder
- (3) Calculate error $e(k) = n_{target} - n_{actual}$
- (4) Incremental PID output: $\Delta u = K_p [e(k) - e(k-1)] + K_i e(k) + K_d [e(k) - 2e(k-1) + e(k-2)]$
- (5) Update control variable $u(k) = u(k-1) + \Delta u$ and convert to pulse frequency $f = u(k)$
- (6) Limit the output and drive the stepper motor
- (7) Wait for the next sampling period $T_s = 50$ ms, return to Step 1

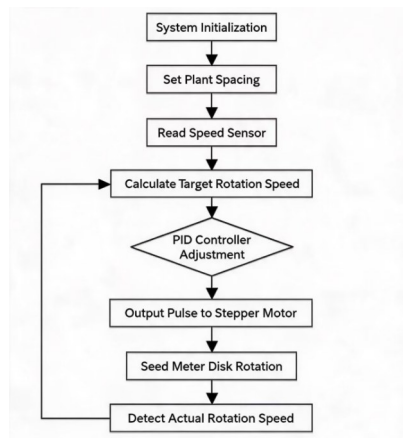


Figure 8 Flowchart of vehicle speed adaptive seeding control

Through Simulink simulation, when the vehicle speed step changes from 0.3 m/s to 0.6 m/s, the response time of the disc rotational speed is about 0.3 s, the overshoot is less than 5%, and the steady-state error is less than 0.5 r/min, meeting the requirements of precision seeding.

6 Conclusion

(1) An inclined disc seed metering mechanism suitable for a small electric intelligent seeding vehicle was designed. Key parameters such as the disc diameter and number of cells were determined. An initial cell determination algorithm based on seed geometric dimensions and a multi-objective iterative optimization algorithm were proposed, obtaining the optimal cell diameter of 8.2 mm and depth of 3.8 mm for soybean seeds, with a theoretical filling success rate of 96.5%.

(2) Through 3D modeling, finite element analysis and ADAMS motion simulation, it was verified that the maximum stress of the metering disc at the maximum rotational speed is 18.5 MPa, indicating a safe and reliable structure. The seed spacing quality index reached 93.2% at a disc speed of 15 r/min, verifying the rationality of the design.

(3) A vehicle speed-seed metering rotational speed adaptive PID control algorithm was developed, featuring fast response and small overshoot, providing a control foundation for intelligent seeding. In the future, a physical prototype will be fabricated for field tests to further optimize the seed clearing device and the wear resistance of the cells.

About the Author

Pengda An, bachelor's degree, research direction: intelligent manufacturing engineering.

Lingling Li, female, Master of Engineering, Associate Professor, mainly engaged in teaching and research of mechanical design and theory.

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