Design and Testing of an Elastic Comb Reciprocating a Soybean Plant-to-Plant Seedling Avoidance and Weeding Device

Shenghao Ye 1, Xinyu Xue 1, Shuning Si 1, Yang Xu 1, Feixiang Le 1, Longfei Cui 2,* and Yongkui Jin 1,*

1 Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China; xuexinyu@caas.cn (X.X.); xuyang01@caas.cn (Y.X.); lefeixiang@caas.cn (F.L.)
2 Key Laboratory of Modern Agricultural Equipment, Ministry of Agriculture and Rural Affairs, Nanjing 210014, China
* Correspondence: cuilongfei@caas.cn (L.C.); jinyongkui@caas.cn (Y.J.)

Abstract: Although there are existing interplant weed control devices for soybeans, they mostly rely on image recognition and intelligent navigation platforms. Simultaneously, automated weed control devices are not yet fully mature, resulting in issues such as high seedling injury rates and low weeding rates. This paper proposed a reciprocating interplant weed control device for soybeans based on the idea of intermittent reciprocating opening and closing of weeding execution components. The device consists of a laser ranging sensor, servo motor, Programmable Logic Controller (PLC), and weeding mechanism. Firstly, this paper explained the overall structure and working principle of the weed control device, and discussed the theoretical analysis and structural design of the critical component, elastic comb teeth. This paper also analyzed the working principle of the elastic comb teeth movement trajectory and seedling avoidance action according to soybean agronomic planting requirements. Then, field experiments were conducted, and the experiment was designed by the quadratic regression general rotation combination experimental method. The number of combs, the speed of the field management robot, and the stabbing depth were taken as the test factors to investigate their effects on the test indexes of weeding rate and seedling injury rate. The experiment utilized a response surface analysis method and designed a three-factor, three-level quadratic regression general rotation combination experimental method. The results demonstrate that the number of comb teeth has the most significant impact on the weeding rate, while the forward speed has the most significant impact on the seedling injury rate. The optimal combination of 29.06 mm stabbing depth, five comb teeth, and a forward speed of 0.31 m/s achieves an optimal operational weeding rate of 98.2% and a seedling injury rate of 1.69%. Under the optimal parameter combination conditions, the machine’s performance can meet the requirements of intra-row weeding operations in soybean fields, and the research results can provide a reference for the design and optimization of mechanical weed control devices for soybean fields.

Keywords: soybean; automation control; interplant weeding; imitation elastic comb teeth; field test

1. Introduction

Soybean is a major food crop in China. During the growth cycle of soybean, weeds in the farmland can have an impact on its growth. Weeds not only compete with soybeans for water, sunlight, nutrients in the soil, and necessary space for growth, but some weeds also easily breed pests and diseases [1]. This affects the actual yield of soybeans and restricts their quality and high yield. To ensure high soybean yield and quality, weed control is a crucial step. With the development of new agricultural technologies, weed control methods are constantly innovating. In addition to primitive manual weeding, methods such as physical and mechanical weeding, chemical weeding, thermal weeding, and biological weeding have emerged. Among them, chemical weeding and physical and mechanical
weeding are more commonly used [2–4]. Other weed control methods are not widely applied due to their high cost, limitations of environmental conditions, and inconsistency with modern green and efficient crop protection concepts. The application of herbicides is the main form of chemical weeding, with advantages such as high efficiency and good weed control effects. However, the long-term use of herbicides not only affects personnel safety and pollutes the natural environment but also causes weeds to develop drug resistance [5]. The healthy and safe method of mechanical weeding can solve this problem. Mechanical weeding can not only improve the yield and quality of soybeans but also adapt to complex farmland environments [6,7].

To achieve efficient and effective weed control in field operations, many researchers have conducted in-depth studies on information-based and intelligent weed control equipment. According to the current research results, mechanical weeding can be divided into inter-row weeding and intra-row weeding [8]. Mohd Taufik Ahmad et al. [9] optimized the rotational tooth structure for mechanical weeding and performed design performance testing. The mechanism was combined with machine vision to detect the position of crops and guide the mechanism in weed removal operations. Wang Gang et al. [10] designed a row weeding device that can locate the position of corn seedlings and avoid them during weeding operations. The device used a comb-toothed weeding execution component. Its average weeding rate is 95.1%, and its average seedling injury rate is 1%.

The inter-row weeding technology has gradually matured, but the removal of intra-row weeds is relatively difficult. This is because there is a risk of damaging soybean plants when removing weeds close to them. Currently, the optimization and innovation of intra-row weeding models have become a hot research topic for many scholars [11,12]. Manuel Pérez-Ruíz et al. [13] researched and developed a low-cost integrated weeding robot. The robot utilizes sensors to measure the distance between seedlings and achieves precise weed control by controlling the opening and closing of miniature hoes. The manual labor required for inter-plant weed control reduced by 57.5%, indicating that this robot can help decrease the traditional manual hoeing labor requirements and perform mechanical weeding in the intercropping areas. C. Cordill et al. [14] designed and conducted experiments on intra-row mechanical weeding in maize fields. They utilized feedback signals from laser sensors to identify weeds and maize plants. They then employed a dual-tine carrier to non-specifically remove weed plants within the row by engaging the soil while circumventing the maize stalks. N.D. Tillett et al. [15] processed crop information accurately using a machine vision system on the notched disk weeding device, allowing blades to cut weeds precisely. Combined intra-row with inter-row cultivation typically removes 80% of weeds. Crop damage was low with no plants killed when operating within the normal levels of commercial growing conditions. Hu Lian et al. [16] designed an intra-row mechanical weeding device based on the principle of residual oscillation motion of the weeding tines. The principle is to utilize the weeding tines to remove intra-row weeds while they swing between the rows. To avoid damaging the crop seedlings, the number of tines can be reduced to decrease the rotation radius. Experimental results showed that at a forward speed of 0.3 m/s, the average seedling injury rate was 2.5%. Chen Ziwen et al. [17] designed a planetary brush-type intra-row weeding mechanical arm for plants with well-developed root systems and easily compacted soil conditions. During operation, it uses planetary gear to drive the circular plate and cut the weeds. The average weeding rate can reach 89.3%, with an average seedling injury rate of 3.5%. Jia Honglei et al. [18] designed a seedling-avoiding and weeding device for use in corn fields, where the weeding component rotates intermittently during weed removal. The average weeding rate of the device was 94.7%, with an average seedling injury rate of 5.9%. In conclusion, the existing structures of intra-row weed control devices are diverse, with the potential for further improvement in the seedling injury rate and weeding rate. In terms of weed identification, the integration of weed control devices with technologies such as image recognition enables the differentiation between weeds and soybean plants before the operation of the weeding mechanism.
Currently, various methods are used for soybean recognition, including laser radar, spectral analysis, image recognition, and mechanical sensing [19–21]. The preparatory tasks for image recognition can be demanding and are influenced by environmental conditions such as lighting and shadows. The accuracy of recognition is frequently impacted by factors such as the complexity of the image background, the similarity between crops and weeds in morphology, and environmental elements [22–25]. Real-time implementation is not feasible with laser radar and necessitates prior data collection. Moreover, it is costly and difficult to apply universally [26]. Mechanical sensing requires demanding characteristics in plant and weed appearances. It is necessary to design the various forms and leaf distributions for different growth stages of plants and weeds. Therefore, it cannot adapt well to complex field environments. Laser ranging sensors (BL-200NMZ, manufactured by BOJKE, headquartered in Shenzhen, China) possess characteristics such as high precision, high speed, and high stability, allowing them to avoid the influence of environmental factors such as light and shadows. Additionally, they have a lower cost and exhibit good performance when used.

To solve the problems of low weeding rate and high seedling injury rate in intra-row weed control devices for soybeans, a reciprocating shape-mimicking elastic comb intra-row weed control device for soybeans was designed in this article. This device considers the growth characteristics and physical features of soybean plants and weeds, along with the agronomic requirements for soybean cultivation. The article utilizes a laser ranging sensor to identify the position of soybean plants and a programmed soybean plant recognition model in the Programmable Logic Controller (PLC) to ascertain whether a plant is a soybean. With input from the robot’s forward speed and the distance between the laser ranging sensor and the weeding execution mechanism, the PLC issues instructions to the servo motor (TSDA-C21B, manufactured by Vacsin, headquartered in Shenzhen, China) to coordinate the avoidance action of the weeding execution component. The structure design of the weeding device, analysis of the motion trajectory of the shape-mimicking elastic comb, field tests combining PLC control technology, and laser recognition of soybean plants model were conducted in this study. The quadratic regression generalized rotary combination test method was designed to verify its operational performance, to provide a reference for the design of the soybean intra-plant weeding device.

2. Materials and Methods

2.1. Weeding Device

The weeding device comprises a weeding mechanism, recognition system, control system, and mobile platform, as shown in Figure 1. The mobile platform, depicted as the field management robot in Figure 1, is primarily responsible for providing the driving force for the advancement of the weeding mechanism and supplying power to the recognition system and control system.

2.1.1. Weeding Mechanism

The reciprocating elastic comb-tooth weeding mechanism is illustrated in Figure 2a. This mechanism primarily includes a servo motor, frame, spindle, guide rail slider, flange disc, connecting rod, fixing rod, combing plate, and elastic comb teeth. The servo motor operates the rotation of the flange disc via the spindle, with the comb plate linked to the connecting rod and fixed rod. When the flange disc propels the connecting rod, the comb plate is restricted to horizontal movement due to the fixed rod and guide rail. The physical appearance of the mechanism is shown in Figure 2b. To reduce seedling damage caused by the weeding mechanism, the elastic comb teeth were designed according to the appearance of soybean plants. This minimizes the likelihood of contact between the elastic comb teeth and the stems and leaves of soybean plants.

In actual operation, the servo driver sends pulse signals to drive the motor to rotate. The operating voltage of the servo driver is 24–80 V, with a peak input current of 50 A, a rated speed of 3000 RPM, and a power of 400 W. The model is TSDA-C21B.
2.1.1. Weeding Mechanism

The main components of the recognition system are two identical laser ranging sensors (BL-200NMQ, manufactured by BOJKE, headquartered in Shenzhen, China). The primary material used in the control system is a SIMATIC S7-200SMART PLC (manufactured by SIEMENS AG, headquartered in Munich, Germany).

The weeding mechanism and laser ranging sensors are suspended underneath the field management robot using lifting and ground-mimicking mechanisms [27], as shown in Figure 3. They are primarily used for weeding during the three-leaf stage of soybeans in the field, with the mimicking mechanism designed to adapt to the uneven surface of the soil. When the intra-row weeding mechanism carries out the weeding operation, it requires the seedling detection system, motion control system, and weed control actuator to work together, as shown in Figure 4. The seedling detection system includes the acquisition, processing, and output of information related to soybean plants and weeds, transmitting the extracted distance data information to the control system. The control system uses the soybean plant recognition model in the PLC to differentiate between soybean plants and weeds. Subsequently, the PLC sends instructions to the servo driver to coordinate the movement of the weeding mechanism, which indirectly causes the comb plate to open and close.

**Figure 1.** Weeding device.

**Figure 2.** Reciprocating elastic comb weeding mechanism: (a) Structural conceptual diagram: 1. servo motor; 2. frame; 3. guide rail slider; 4. spindle; 5. flange disk; 6. connecting rod; 7. fixing rod; 8. combing plate; 9. elastic comb teeth; (b) actual picture.

2.1.2. Recognition System and Control System

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Figure 3. Weed control actuator and sensor position hanging diagram.

Figure 4. Sketch of the work of the intra-plant weeding mechanism.

2.2. Control Methods and Principles of Operation

2.2.1. Control Methods

Due to the impact of environmental conditions, such as light and shadows, on image recognition sensitivity, mechanical sensors are not suitable for complex field environments and other issues. In this study, laser ranging sensors are used to identify soybean plants, so as to locate the soybean plants earlier. This enables the weeding mechanism to avoid the soybean plants in time.

Before the operation, based on the field conditions of soybeans, the laser ranging sensors are placed in front of the weeding mechanism. The BL-200NMZ model of laser ranging sensor has a range between 120 mm and 280 mm. The inter-row spacing of soybean plants is 300 mm. Therefore, two sensors can be placed on one side of the soybean plants, maintaining a horizontal distance of 200 mm from the weeding mechanism, as illustrated in Figure 5, to avoid interference caused by contact between soybean leaves and the sensors. During the operation, the weeding mechanism moves forward along with the field management robot while conducting the weeding task. When the PLC receives distance data transmitted by the laser range sensor that conforms to the identification...
model, the PLC will synchronize the control of the comb plate to expand to both sides to avoid the soybean plants.

![Sensor and weeding control actuator positioning diagram.](image)

The response time for the laser ranging sensor to collect distance data is 1.5 ms. The response time from the time the sensor collects data to the time the soybean plant is recognized by the soybean recognition model is approximately 5 ms.

Two laser ranging sensors are installed to facilitate the soybean plant recognition model, one above and one below. The sensors transmit analog signals to the PLC in real-time. Under the conditions of the soybean plant recognition model, the PLC will integrate the forward speed of the robot and the distance between the sensors and the weeding mechanism, and then transmit synchronized instructions to the servo motor controller. The servo motor controller will send pulses to rotate the servo motor, thereby driving the spindle and flange disk to rotate. As the comb plate is linked to the connecting rod and fixed rod, when the flange rotates to drive the connecting rod, the comb plate can only expand or close due to the fixed rod. This achieves the switching between weeding status → avoiding seedling status → weeding status and completing the weeding operation between soybean plants.

While in operation, the lifting mechanism of the equipment gently lowers the weeding device between the soybean plants. The elastic teeth of the weeding mechanism then penetrate the soil surface at a specific depth. The field management robot then drives the comb teeth, which brush away the weed roots and stems from the soil. They can also cut or pull the roots and stems of weeds to achieve the desired weeding effect.

2.2.2. Soybean Plant Recognition Model

The mechanical weeding of soybean plants is most effective during the three-leaf stage. During this stage, soybean plants exhibit a diameter of 4-5 mm, while surrounding weeds tend to be shorter with stem diameters generally below 3 mm. The discrepancy in both diameter and height between soybean plants and the surrounding weeds is significant. The average height of soybean plants in the three-leaf stage is about 250 mm, while the height of weeds is about 70–100 mm, with some exceeding 150 mm. Combined with the planting spacing requirements for soybean plants, the plant distance should be 100 mm. Three identification rules are summarized; namely, diameter, height, and spacing. In order to identify an object’s height, the employment of two laser ranging sensors is necessary. This requirement is satisfied when both sensors detect the object. Furthermore, the recognition model for soybean plants has been established within the PLC.

The laser ranging sensor exports point cloud data, which is shown in Figure 6. These data can identify different object diameters, but they may also contain stray points that
fall outside the range and are considered invalid. The laser ranging sensor has a range of \( d_{\text{min}} - d_{\text{max}} \). Therefore, the algorithm processes the data as follows:

\[
f(x) = \begin{cases} 
    d_{\text{min}} \leq d \leq d_{\text{max}} \text{ and } |d_0 - d| \leq m_1, & x = 1 \\
    d \leq d_{\text{min}}, & x = 0 \\
    d \geq d_{\text{max}}, & x = 0
\end{cases}
\]  

(1)

where \( d \) is the distance between the sensor and the target object; \( d_0 \) is the distance between the sensor and the target object for the next acquisition; \( d_{\text{max}} \) is the maximum range of the sensor; \( d_{\text{min}} \) is the minimum range of the sensor; \( m_1 \) is the difference between the distance data collected by the sensor during the last acquisition and the distance data to be collected during the next acquisition.

**Figure 6.** Distance diagram of different measured objects’ diameters.

Below is the definition of the soybean plant recognition model.

**Figure 7** is a schematic diagram for measuring the diameter and the formula for the diameter condition is as follows:

\[D = v_i t_i\]  

(2)

\[
f(c) = \begin{cases} 
    d_{\text{min}} \leq x_1 \leq d_{\text{max}} & c = 1 \\
    x_1 \leq d_{\text{min}}, & c = 0 \\
    x_1 \geq d_{\text{max}}, & c = 0
\end{cases}
\]  

(3)

\[
f(c) = \begin{cases} 
    d_{\text{min}} \leq x_2 \leq d_{\text{max}} \text{ and } |x_2 - x_1| \leq m_1, & c = 2 \\
    x_2 \leq d_{\text{min}}, & c = 0 \\
    x_2 \geq d_{\text{max}}, & c = 0
\end{cases}
\]  

(4)

\[c = \sum_{i=1}^{n} x_i, d_{\text{min}} \leq x_n \leq d_{\text{max}} \text{ and } |x_{n+1} - x_n| \leq m_1\]  

(5)

where \( D \) is the diameter of the target object; \( v_i \) is the speed at which the field management robot is moving; \( t_i \) is the time taken to detect the diameter of the target object; \( x_1 \) is the collect distance data from the previous record; \( x_2 \) is the collect distance data from the next record; \( d_{\text{max}} \) is the maximum range of the sensors in the experiment; \( d_{\text{min}} \) is the minimum range of the sensors in the experiment; \( m_1 \) is the difference between the distance data collected by the sensor during the last acquisition and the distance data to be collected during the next acquisition; and \( c \) is the recorded value.
where $d_{hs}$ is the distance data of the target object collected by the upper sensor; $x_{hs}$ is the position of the upper sensor when the target object is detected by the upper sensor; $d_{hx}$ is the distance data of the target object collected by the lower sensor; $x_{hx}$ is the position of the lower sensor when the target object is detected by the lower sensor; $x_{h}$ is the difference in position of the two sensors in the horizontal direction; and $m_2$ is the maximum value of the position in the horizontal direction.

Figure 8 is a schematic diagram for measuring the height, and the formula for the height condition is as follows:

$$f(x_h) = \begin{cases} |x_{hs} - x_{hx}|, & x_h \leq m_2 \\ d_{min} \leq d_{hs} \leq d_{max} \\ d_{min} \leq d_{hx} \leq d_{max} \end{cases}$$  \tag{6}$$

where $d_{hs}$ is the distance data of the target object collected by the upper sensor; $x_{hs}$ is the position of the upper sensor when the target object is detected by the upper sensor; $d_{hx}$ is the distance data of the target object collected by the lower sensor; $x_{hx}$ is the position of the lower sensor when the target object is detected by the lower sensor; $x_{h}$ is the difference in position of the two sensors in the horizontal direction; and $m_2$ is the maximum value of the position in the horizontal direction.

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Figure 9 is a schematic diagram for measuring the spacing, and the formula for the spacing condition is as follows:

$$f(x_1) = |x_{1q} - x_{1h}|, \quad a \leq x_1 \leq b$$  \tag{7}$$

where $x_{1q}$ represents the position of the previous soybean plant; $x_{1h}$ represents the position of the subsequent soybean plant; $x_1$ represents the spacing between the previous and subsequent soybean plants; $a$ represents the minimum threshold for the spacing between the previous and subsequent soybean plants; and $b$ represents the maximum threshold for the spacing between the previous and subsequent soybean plants.
The PLC receives distance data from the laser ranging sensor within a specified range and checks if the difference between two consecutive recordings is less than \( m_1 \) (usually 9). If the difference is less than \( m_1 \), a record value of 1 is assigned. Subsequent readings within the next 10 ms will either increase the record value by 1 if they fall within range or reset it to 0 if they do not. A record value of 0 or 1 indicates that no object or weed has been detected. However, if the record value is 2 or higher, it meets the diameter condition.

For height condition judgment, a threshold of 9 mm \( (m_2) \) is set due to the straight stem of the soybean plant. The height condition is fulfilled when the upper sensor detects distance data and the lower sensor records a value of 2 or more within the threshold range, or vice versa.

In line with agricultural planting guidelines, soybean plants should be spaced 100 mm apart. Once the first plant is identified as a soybean plant, a spacing condition will be introduced. In order to reduce spacing errors in planting, the threshold is set to 30 mm. Currently, the specified threshold values are \( a = 7 \) and \( b = 13 \).

The height difference between soybean plants and weeds is noticeable, especially during the three-leaf stage of soybean growth, when the weeds surrounding the soybean plants are often shorter. To minimize misidentification in cases where soybean plant diameters are around 3 mm with a record value of 1 and when height and spacing requirements are met, the subject is classified as a soybean plant.

Additionally, given the intricacies of the field environment, if the lower laser ranging sensor detects a leaf while the upper sensor detects an object, adjustments are necessary. For instance, at a speed of 0.3 m/s, when the lower sensor \( (c = 2) \) meets the diameter condition, a restriction of \( c \) less than 4 should be implemented, as shown in Figure 10. This modification ensures that the soybean plant recognition model no longer confuses soybean leaves for stems. Typically, at the three-leaf stage, the minimum leaf height of a soybean plant is 90 mm, while the laser ranging sensor detects at 70 mm, minimizing interference with leaf detection.

**Figure 9.** Distance collecting of soybean plants schematic diagram.

**Figure 10.** Soybean leaf disturbance schematic diagram.
3. Design of Weeding Execution Mechanism and Control System

3.1. Weeding Execution Mechanism

3.1.1. Determining Execution Mechanism Parameters

The study shows that soybeans generally enter the trifoliate period 10–12 days after planting, which is the best time for mechanical weeding. According to the agronomic requirements of soybean planting, the plant distance should be 100 mm, and the row spacing should be 300 mm. The weeds in the soybean field mainly consist of dog tail grass and barnyard grass, as well as many annual broadleaf weeds. During the survey of soybean fields in the trifoliate period, it was found that the average height of soybeans was about 250 mm, with stem diameters ranging from 4 to 5 mm. The root system includes main roots and lateral roots, with the main roots being vertically stout and measuring between 90 and 100 mm in length, with a distribution range of approximately 80 mm. Weeds are generally shorter in height, around 70–100 mm, and have stem diameters generally less than 3 mm. Many weeds are in the germination stage. For example, barnyard grass has only one slender main root. The root length ranges from 100 to 400 mm, with a distribution range of about 30 mm.

After observing and analyzing various weed removal implements, it was found that during this period, elastic comb teeth can effectively remove weeds by cutting or pulling out their roots from the soil surface. Additionally, it has a low seedling injury rate, causing only distortion when encountering soybean plants. Furthermore, based on the appearance of soybean plants, the elastic comb teeth were designed to mimic their shape, reducing the likelihood of contact between the elastic comb teeth and soybean stems and leaves, and further reducing the seedling injury rate. To meet the weeding requirements for a set of soybean plants, this study sets the length of the two comb teeth plates in the soybean intra-row weeding mechanism to 1300 mm. Using imitated elastic comb teeth installed on the 1300 mm × 200 mm comb teeth plate, each comb teeth plate is equipped with five elastic comb teeth. Based on the average height of soybean plants during the three-leaf stage, which is 250 mm, this research set the total height of the comb teeth to be 290 mm. Additionally, the distribution range of the root systems of both soybean plants and weeds was obtained through the survey conducted in this study. To increase the weeding area, the distance between the comb teeth was set to 20 mm. The material of the comb teeth in this research is spring steel.

During the design process of the comb teeth plate, considerations were given to how the arrangement of the comb teeth plate would affect factors such as seedling avoidance response time, power consumption, weeding efficiency, and other factors. Due to the small plant spacing of soybeans, to ensure the forward speed of the field management robot, it is required to complete seedling avoidance within each cycle as quickly as possible. The arrangement of the comb teeth on the comb teeth plate needs to satisfy the characteristics of weeding, maximize contact with the soil surface, and improve weeding efficiency. During the design process, it was found that the more comb teeth there are, the larger the contact area with the soil, resulting in increased working resistance. Therefore, it is necessary to achieve the weeding requirements with fewer comb teeth. It is important to start with the distance between the comb teeth and the shape of the comb teeth bottom, while also specifying the range of intra-row weeding. Taking reference from other weeding components, the elastic bottom of the comb teeth is modified into a hook shape for easy insertion into the soil. Moreover, after insertion, it can effectively cut weed roots. By rotating each comb tooth at a certain angle, the cutting area can also be increased, as shown in Figure 11.

3.1.2. Trajectory Analysis for Seedling Avoidance

According to the seedling avoidance principle described in this article, during the operation of the intra-row weeding mechanism, it is necessary to switch between the weeding state, the seedling avoidance state, and the weeding state. When the weeding mechanism is in the weeding phase, the two comb teeth plates are closed. The elastic comb
teeth below the comb teeth plates penetrate into the soil, sweeping through the soil on both sides of the soybean plants and between the rows. This cuts off the weed roots or pulls them out of the soil. During the seedling avoidance phase, the flanged disc rotates to open the two comb teeth plates outward. After passing through the soybean plants, the disc rotates again to close the comb teeth plates, completing the seedling avoidance operation and entering the next weeding state. Analyzing the intra-row seedling avoidance and weeding operations, the movement trajectory of the comb teeth plates under the influence of the field management robot’s advancement is shown in Figure 12. In order to protect the soybean plants and avoid direct contact between the elastic comb teeth and the plants, a protection zone with a range of 20 mm around the soybean plant stems is designated based on the range of the soybean plant roots. During operation, considering the canopy width of the soybean plants, efforts should be made to minimize the possibility of the comb teeth touching the stems and leaves of the soybean plants. Through the imitation-shaped structure, the stems and leaves of the soybean plants can be effectively protected.

![Figure 11. Imitation elastic comb teeth.](image)

![Figure 12. Schematic diagram of the movement trajectory of the weeding mechanism.](image)

In brief, the seedling avoidance stage of the intra-row weeding mechanism is divided into three steps. Initially, the laser ranging sensor detects the soybean plants, following which the PLC sends instructions to the servo motor through the soybean plant recognition model, regulating the expansion of the comb teeth plates to their maximum displacement. In the second step, the comb teeth plates on both sides remain at the maximum displacement and pass over the soybean plants. In the third step, the elastic comb teeth beneath the comb teeth plates close again after passing through the soybean plants, continuing the weeding operation. Because the elastic comb teeth require time during the process of expansion and closure, during the seedling avoidance operation, the comb teeth need to be expanded at a...
distance in front of the soybean plants’ safe zone. After passing through the soybean plants, they should also close at a certain distance. The movement trajectory of the comb teeth plates is shown in Figure 13. The comb teeth plates expand from point a, reach point b in the maximum displacement state, maintain this state until point c, then begin to retract and close at point d. During this process, the following points should be noted: (1) During the rotation phase, the motor should rotate quickly to ensure the rapid opening or closing of the comb teeth plates, thereby reducing damage to the seedlings. (2) During the pause phase, the motor should stop rotating to ensure that the comb teeth maintain their maximum expansion distance. (3) During the weeding phase, the motor should be in a brake state to keep the comb teeth closed for intra-row weeding.

![Figure 13. Weeding mechanism movement trajectory analysis diagram.](image)

During the closure phase, the trajectory and absolute velocity $v_0$ of the comb plate are:

$$\begin{cases} x = v \cdot t \\ y = 0 \\ v_0 = v \end{cases} \quad (8)$$

The trajectories and absolute velocities $v_1$ for the unfolding and closing phases are:

$$\begin{cases} x = v \cdot t \\ y = v_m \cdot t \\ v_1 = \sqrt{v + v_m} \end{cases} \quad (9)$$

The trajectory and absolute velocity $v_2$ of the seedling avoidance phase are:

$$\begin{cases} x = v \cdot t \\ y = r \\ v_2 = v \end{cases} \quad (10)$$

where $v$ represents the forward speed of the field management robot, m/s; $v_m$ represents the linear speed of the motor rotation, and m/s; $t$ represents the time, s.

At this moment, the segment analysis is:

$$\begin{cases} t_1 = \frac{L_1}{v} \\ t_2 = \frac{L_2}{v} \\ t_3 = \frac{L_3}{v} \\ t_4 = \frac{L_4}{v} \end{cases} \quad (11)$$

$$L_1 + L_2 + L_3 + L_4 = L \quad (12)$$

where $t_1$ represents the clockwise rotation stage motor rotation time, s; $t_2$ represents the pause stage motor braking time, s; $t_3$ represents the counterclockwise rotation stage motor rotation time, s; $t_4$ represents the motor braking state time, s; $L_1$ represents the clockwise rotation stage field management robot traveling distance, mm; $L_2$ represents the pause stage field management robot traveling distance, mm; $L_3$ represents the counterclockwise rotation stage field management robot traveling distance, mm; $L_4$ represents the counterclockwise rotation stage field management robot traveling distance, mm; $L$ represents the total traveling distance of the field management robot.
stage field management robot traveling distance, mm; \( L_4 \) represents the motor braking state field management robot traveling distance, mm; \( L \) represents soybean planting plant spacing, mm; \( v \) represents the field management robot forward speed, m/s.

Based on the movement status of the comb teeth plates and the structural characteristics of the flange disc and connecting rod in the weeding mechanism, the rotation pattern of the disc is determined by the pulses sent by the servo driver to the servo motor. When the comb teeth plates are expanded to their maximum spacing, the distance between the lower teeth is 20 mm, and at this time, the position pulse sent by the servo driver is 300. During the pause phase, the position pulse is maintained. When rotating counterclockwise, the position pulse sent by the servo driver is 0, and the comb teeth plates will close again.

At this time:
\[
t_1 = t_3 = \frac{\pi}{2\omega}
\]

\[
\omega = 2\pi n
\]

where \( \omega \) is the motor rotational angular velocity, rad/s and \( n \) is the motor rotational speed, r/s.

Substituting Equation (14) into Equation (13), it can be inferred:
\[
t_1 = t_3 = \frac{1}{4n}
\]

Combining Equations (11), (12) and (15), it can be known:
\[
t_2 = \frac{L - L_4}{v} - \frac{1}{2n}
\]

From Equation (15), it can be seen that the trajectory of the elastic comb teeth is determined by the motor rotational speed, the forward speed of the field management robot, the distance traveled by the field management robot when the motor is in the braking state, and the spacing of the soybean plants. The rotational speed of the servo motors and the forward speed of the field management robot can be controlled to adapt to different plant spacing and crop protection areas during weeding and seedling avoidance operations.

3.1.3. Design of Seedling Avoidance Systems

The relationship between the weeding mechanism, laser ranging sensor, and soybean plant positions is shown in Figure 14. The laser ranging sensor, positioned at the front end of the frame, is used in conjunction with elastic comb teeth to detect the position of soybean plants. During operation, when the sensor detects distance data that do not meet the soybean recognition model, the comb teeth plate will close to remove intra-row weeds. If the sensor detects data that satisfy the soybean recognition model, the PLC will transmit a signal to the servo controller. This controls the servo motor to rotate and drive the comb teeth plate to expand synchronously for seedling avoidance. After the seedling avoidance process is complete, according to instructions, the comb teeth plate will close back to its original position, waiting for the next seedling avoidance cycle.

![Figure 14. Laser ranging sensor installation location schematic.](image-url)
In conclusion, considering the soybean plant spacing and selected parameters of the laser ranging sensor, the servo motor’s delayed running time should satisfy the following relationship:

$$\Delta t = \frac{L_6 - \frac{L_1 + L_2 + L_3}{2}}{v} + t_0$$

where $\Delta t$ represents the delayed running time of the servo motor, $s$; $L_6$ represents the installation distance of the weeding bullet teeth, and the laser sensor, $mm$; and $t_0$ represents the response time of the motor, $s$.

3.2. Control Strategy and Control Steps

The control system adopts SIMATIC S7-200 SMART PLC as the control core. The control system physical diagram is shown in Figure 15.

![Control box physical diagram.](image)

The control strategy is shown in Figure 16. Before the weeding starts, the servo motor is initialized. As it passes a soybean plant, the control system receives distance information from the laser ranging sensor. Using the soybean recognition model, the PLC identifies whether it is a soybean plant and computes the delay time for initiating the unfolding of the soybean plant. The PLC also reads the forward speed information of the field management robot in real-time and sends the execution command to the servo driver through the RS485 communication Modbus protocol. When the comb plate reaches the safety range of the soybean plant, it starts to unfold for seedling avoidance. After passing by the soybean plant, it closes again to continue the weeding operation.

The distance information detected by the laser ranging sensor is outputted via the analog output lines (+) and (−). To address the instability of the data output resulting from prolonged analog voltage output and the extended operational requirements of the mechanical weeding device, analog current output is utilized.

The analog output line (+) of the two distance sensors is connected to the (I0+) and (I1+) input ports of the EM AE04 (analog input module), respectively, while the analog output line (−) is connected to the (I0−) and (I1−) input ports of the EM AE04 (analog input module). The laser ranging sensor is calibrated, and the function algorithm for converting analog quantity to actual distance is programmed in the PLC. Subsequently, the software’s data block selects the EM AE04, and opens analog input channels (0) and (1) with settings for analog current and unfiltered input.

The PLC utilizes its built-in RS485 communication interface. One end of the RS485 converter is linked to the PLC’s RS485 communication interface, while the other end is connected to the RS485 network port of the servo driver. Commands are transmitted to the servo driver through the RS485 network port, and the Modbus protocol is established in the software to facilitate communication between the PLC and the servo driver. The servo driver is connected to the servo motor via the motor encoder line and the motor power
line. During seedling avoidance actions, the servo driver dispatches pulse commands to the servo motor, enabling it to execute the necessary operations.

![Flowchart of one cycle of seedling avoidance action.](image)

In addition, the laser ranging sensor, lifting mechanism, PLC, and servo driver all require a 24 V DC power supply. They can be powered directly through the 24 V power supply port of the field management robot.

4. Field Test

4.1. Test Condition

The test was conducted at the Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs. The test site was a soybean field planted by itself, with a total length of 20 m and a width of 10 m, two fields in total. The intra-row weeding device is installed under the field management robot, as shown in Figure 17. During the forward movement of the field management robot, the weeding device performs intra-row weeding on soybean plants. Each experiment was conducted on a single row of soybean plants, as shown in Figure 18. In the experiment, the average height of the soybean plants was 250 mm, with a diameter of 4–5 mm. The weeds consisted of natural shepherd’s purse, quinoa, and barnyard grass, with a diameter between 0.5 and 2 mm, and roots less than 30 mm deep. As shown in Figure 19, it illustrates the weeding effect before and after the experiment.

![Weed control device installation position.](image)
they can be powered directly through the 24 V power supply. They are capable of operating at a forward speed of 0.05 m/s with a total length of 20 m and a width of 10 m, two in total. The weeding device is installed under the field management robot, as shown in Figure 17. During the experiment, the lifting mechanism, PLC, and servo driver all work harmoniously to make the robotic field management robot perform intra-row weeding on soybean plants, as shown in Figure 18. In the experiment, the average height of the soybean plants was 250 mm, with a diameter of 4–5 mm. The weeds consisted of natural shepherd’s purse, quinoa, and barnyard grass, with a diameter between 0.5 and 2 mm, and roots less than 30 mm deep. As shown in Figure 19, it illustrates the weeding effect before and after. Observation of soybean plants in soybean fields during the experiment showed that the stems and leaves of the soybean plants were mostly intact. Prior to the experiment, only soybean plants with normal stems and leaves were included in the statistics. During the experiment, apart from the weeding execution mechanism, the laser ranging sensor, wheel, and field management robot did not come into contact with the soybean plants. Therefore, throughout the field experiment, only the weeding elastic comb teeth may have affected the stems and leaves of the soybean plants.

### 4.2. Test Program

According to the quadratic regression combination design method, a three-factor and three-level quadratic regression general rotational design has been selected. The factors of stabbing depth (the depth of the combs into the soil), number of comb teeth, and forward speed have been selected, with the weeding rate and seedling injury rate as the experimental indicators. The determination of seedling injury is based on the actual damage to soybean stems and leaves caused by the elastic comb teeth.

The number of damaged soybean plants is counted manually, and the weeding rate is calculated simultaneously. During manual counting, the process is repeated three times. If the difference in the number of weeds is not significant, the average value is taken. If there is a significant difference among the three results, the counting is redone. The count is considered as the initial number of weeds before the experiment. After each round of experiments, the same method is used for counting, and the count obtained is considered as the number of weeds after the experiment.

The size of the weed search area is determined based on the weeding method. As it is intra-row weeding, only the weeds within 100 mm of the soybean plants are counted.

The formulas for calculating the seedling injury rate and weeding rate are as follows:

\[
R_{c} = \left(1 - \frac{H}{Q}\right) \times 100\% \tag{18}
\]
\[ R_s = \frac{M_h}{M_q} \times 100\% \] (19)

where \( R_s \) represents the seedling injury rate; \( M_h \) represents the number of seedlings damaged after the weeding operation; \( M_q \) represents the number of soybean seedlings before the weeding operation; \( R_C \) represents the weeding rate; \( Q \) represents the number of weeds before the weeding operation; and \( H \) represents the number of weeds after weeding operation.

The study conducted the quadratic regression universal center of rotation design test using Design-Expert 8.05b. Table 1 shows the factors and levels, while Table 2 presents the testing protocol and results. The stabbing depth is established through prior examination of the external traits of soybean plants and weeds. At the three-leaf stage, soybean plants typically have a root depth of approximately 150 mm, whereas the roots of the surrounding weeds generally reach only about 30 mm deep. Therefore, the stabbing depth is determined to be 20–40 mm. The number of comb teeth is determined based on the weeding range. The inter-row weeding range around soybean plants is 100 mm, and a weeding range of 91 mm can be achieved with four comb teeth. Hence, the number of comb teeth is determined to be 3–5. The forward speed is determined based on the forward speed adopted by the soybean recognition model during identification. The soybean plant recognition model achieves a higher recognition rate at a forward speed of 0.3 m/s. Therefore, the forward speed of the weeding mechanism is set to be 0.2–0.4 m/s.

**Table 1. Test factors and level.**

<table>
<thead>
<tr>
<th>Level</th>
<th>Stabbing Depth/mm</th>
<th>Number of Comb Teeth</th>
<th>Forward Speed/(m s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>4</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>5</td>
<td>0.4</td>
</tr>
</tbody>
</table>

**Table 2. Test program.**

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Stabbing Depth/mm</th>
<th>Number of Comb Teeth</th>
<th>Forward Speed/(m s(^{-1}))</th>
<th>Weeding Rate/%</th>
<th>Seedling Injury Rate/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>4</td>
<td>0.3</td>
<td>91.24</td>
<td>1.18</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>4</td>
<td>0.3</td>
<td>92.17</td>
<td>1.70</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>3</td>
<td>0.4</td>
<td>82.95</td>
<td>5.17</td>
</tr>
<tr>
<td>4</td>
<td>40</td>
<td>4</td>
<td>0.3</td>
<td>93.09</td>
<td>2.91</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>5</td>
<td>0.3</td>
<td>97.70</td>
<td>1.69</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>4</td>
<td>0.3</td>
<td>92.17</td>
<td>1.91</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>5</td>
<td>0.4</td>
<td>98.62</td>
<td>5.71</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>3</td>
<td>0.2</td>
<td>79.26</td>
<td>0.00</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>4</td>
<td>0.2</td>
<td>92.63</td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>5</td>
<td>0.4</td>
<td>96.77</td>
<td>3.51</td>
</tr>
<tr>
<td>11</td>
<td>20</td>
<td>5</td>
<td>0.2</td>
<td>97.70</td>
<td>0.00</td>
</tr>
<tr>
<td>12</td>
<td>30</td>
<td>3</td>
<td>0.3</td>
<td>82.03</td>
<td>1.14</td>
</tr>
<tr>
<td>13</td>
<td>30</td>
<td>4</td>
<td>0.4</td>
<td>92.17</td>
<td>1.83</td>
</tr>
<tr>
<td>14</td>
<td>40</td>
<td>5</td>
<td>0.2</td>
<td>98.62</td>
<td>0.00</td>
</tr>
<tr>
<td>15</td>
<td>30</td>
<td>4</td>
<td>0.3</td>
<td>93.09</td>
<td>1.16</td>
</tr>
<tr>
<td>16</td>
<td>20</td>
<td>3</td>
<td>0.4</td>
<td>79.72</td>
<td>2.89</td>
</tr>
<tr>
<td>17</td>
<td>40</td>
<td>3</td>
<td>0.2</td>
<td>82.03</td>
<td>0.00</td>
</tr>
<tr>
<td>18</td>
<td>30</td>
<td>4</td>
<td>0.3</td>
<td>93.09</td>
<td>1.19</td>
</tr>
<tr>
<td>19</td>
<td>30</td>
<td>4</td>
<td>0.3</td>
<td>92.63</td>
<td>0.59</td>
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<tr>
<td>20</td>
<td>30</td>
<td>4</td>
<td>0.3</td>
<td>93.09</td>
<td>1.15</td>
</tr>
</tbody>
</table>
Determination of the total number of tests \( N \):

\[
N = m_c + 2p + m_o
\]  

where \( p \) represents the number of test factors (\( p = 3 \)); \( m_c \) represents the number of \( 2p \)-type tests (\( m_c = 8 \)); and \( m_o \) represents the number of central test points.

For the total number of tests, \( N = 20 \).

4.3. Analysis of Test Results

According to the principle of the quadratic regression universal center of rotation design, the quadratic regression mathematical model obtained from this experiment is:

\[
y = b_0 + \sum_{j=1}^{3} b_j x_j + \sum_{i<j}^{3} b_{ij} x_i x_j + \sum_{j=1}^{3} b_{jj} x_j^2 \ldots
\]  

where the constant term \( b_0 \) responds to the average effect of each factor at the zero level; the primary terms \( b_1, b_2, \) and \( b_3 \) respond to the effect of a single factor; the interaction terms \( b_{12}, b_{13}, \) and \( b_{23} \) respond to the interaction effect between the factors; and the secondary terms \( b_{11}, b_{22}, b_{33} \) respond to the diminishing reward effect of each factor.

The study applied the Design-Expert 8.0.5b software to perform the regression analysis on the experimental results in Table 2. The experiment screened out the more significant factors and obtained the quadratic polynomial regression models for the weeding rate (\( R_C \)) and seedling injury rate (\( R_S \)), as shown in Equation (21). The significance of these models was then tested, and the results were presented in Table 3.

\[
\begin{align*}
R_C &= 1.74 + 0.44A + 31.86B + 15.13C - 0.04AB + 0.17AC - 2.88BC - 0.0038A^2 - 2.68B^2 - 14.66C^2 \\
R_S &= 10.64 - 0.66A - 2.56B + 8.80C - 0.00096AB + 0.56AC + 1.45BC + 0.0092A^2 + 0.29B^2 - 20.53C^2
\end{align*}
\]  

where \( A, B, \) and \( C \) represent the horizontal values of stabbing depth, number of comb teeth, and forward speed, respectively.

Table 3. Significance test of test factors on weeding rate and seedling injury rate.

<table>
<thead>
<tr>
<th>Variance Source</th>
<th>Degree of Freedom</th>
<th>Sum of Squares</th>
<th>Mean Square</th>
<th>( F ) Value</th>
<th>( p ) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>9</td>
<td>754.68</td>
<td>48.38</td>
<td>83.85</td>
<td>5.38</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>11.23</td>
<td>3.87</td>
<td>11.23</td>
<td>3.87</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>695.73</td>
<td>0.29</td>
<td>695.73</td>
<td>0.29</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>0</td>
<td>36.54</td>
<td>0</td>
<td>36.54</td>
</tr>
<tr>
<td>AB</td>
<td>1</td>
<td>1.30</td>
<td>0.00074</td>
<td>1.30</td>
<td>0.00074</td>
</tr>
<tr>
<td>AC</td>
<td>1</td>
<td>0.24</td>
<td>2.52</td>
<td>0.24</td>
<td>2.52</td>
</tr>
<tr>
<td>BC</td>
<td>1</td>
<td>0.66</td>
<td>0.17</td>
<td>0.66</td>
<td>0.17</td>
</tr>
<tr>
<td>A(^2)</td>
<td>1</td>
<td>0.39</td>
<td>2.34</td>
<td>0.39</td>
<td>2.34</td>
</tr>
<tr>
<td>B(^2)</td>
<td>1</td>
<td>19.77</td>
<td>0.23</td>
<td>19.77</td>
<td>0.23</td>
</tr>
<tr>
<td>C(^2)</td>
<td>1</td>
<td>0.059</td>
<td>0.12</td>
<td>0.059</td>
<td>0.12</td>
</tr>
<tr>
<td>Residual</td>
<td>10</td>
<td>1.96</td>
<td>3.29</td>
<td>0.20</td>
<td>0.33</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>5</td>
<td>0.93</td>
<td>2.67</td>
<td>0.19</td>
<td>0.53</td>
</tr>
<tr>
<td>Pure error</td>
<td>5</td>
<td>1.03</td>
<td>0.63</td>
<td>0.21</td>
<td>0.13</td>
</tr>
<tr>
<td>Cor total</td>
<td>19</td>
<td>756.64</td>
<td>51.67</td>
<td>51.67</td>
<td>51.67</td>
</tr>
</tbody>
</table>

\( A, B, \) and \( C \) are the horizontal values of stabbing depth, number of comb teeth, and forward speed, respectively, while \( R_C \) is the weeding rate and \( R_S \) is the seedling injury rate.

As observed in Table 3, both regression models are highly significant \((p < 0.0001)\), and the misfit terms are all greater than 0.05, indicating a high degree of fit for the regression model. This suggests that the model accurately reflects the relationship between the test indexes of the weeding device and the three factors.
The analysis of the F value in Table 3 indicates that the test factors had an impact on the weeding rate in the following descending order: the number of comb teeth, stabbing depth, and forward speed. Similarly, the test factors affected the seedling injury rate in descending order of forward speed, stabbing depth, and number of comb teeth. To further examine the effects of the test factors and the interaction between them on the test indexes, response surface analysis was conducted. This involved fixing one of the test factors at the zero level and investigating and analyzing the interaction of the other two factors, as well as determining the optimal parameter ranges. The results of this analysis are illustrated in Figure 20.

Figure 20. Response surface analysis: (a) The response surfaces of the weeding rate at different numbers of comb teeth and stabbing depth. (b) The response surfaces of seedling injury rate at different forward speeds and stabbing depth.

4.4. Optimal Operating Parameter Solution

Based on the aforementioned research analysis and agronomic requirements, this study aimed to maximize the weeding rate and minimize the seedling injury rate for the weed control device. Since the weeding range is 100 mm, a weeding range of 115 mm can be achieved with five comb teeth. Therefore, the experiment set the following constraints:

\[
\begin{align*}
\max R_c(A, B, C) \\
\min R_s(A, B, C) \\
20 \text{ mm} \leq A \leq 40 \text{ mm} \\
B = 5 \\
0.2 \text{ m/s} \leq C \leq 0.4 \text{ m/s}
\end{align*}
\]

To find the optimal solution for the three factors, the regression model was optimally solved using the optimization-seeking module of the Design-Expert 8.0.5b software.

After optimizing the regression model using the optimization module of the Design-Expert 8.0.5b software, the optimal parameter combination was obtained as follows: stabbing depth of 29.06 mm, number of comb teeth of five, and forward speed of 0.31 m/s. Correspondingly, the weeding rate is 98.2%, and the seedling injury rate is 1.69%.

The parameter combinations were validated by five replicated tests, and the weeding rate and seedling injury rate were used as the test indexes for validation. The test results obtained are shown in Table 4.
Table 4. Verification scheme and results.

<table>
<thead>
<tr>
<th>Stabbing Depth/mm</th>
<th>Number of Comb Teeth</th>
<th>Forward Speed/(m \cdot s^{-1})</th>
<th>Weeding Rate/%</th>
<th>Seedling Injury Rate/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>29</td>
<td>5</td>
<td>0.3</td>
<td>97.24</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>97.24</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>96.77</td>
<td>1.17</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>98.16</td>
<td>2.30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>97.70</td>
<td>1.70</td>
</tr>
</tbody>
</table>

When the stabbing depth of the elastic comb teeth is 29 mm, the number of comb teeth is five, and the forward speed of the field management robot is 0.3 m/s. The experimental results are close to the optimized results, meeting the requirements for intra-row weed control in soybeans.

5. Discussion

This study observed that the response surface of the weeding rate presents a convex shape. From the color trend and steepness of the response surface, it can be determined that the number of comb teeth had a more significant impact on $R_C$ than the stabbing depth. A significant part of the reason for this lay in the fact that when counting the number of weeds, only weeds within a 100 mm radius around the soybean plant were tallied. However, with five combs, the coverage extended to 115 mm. With four combs, it reached 91 mm, and with three combs, it only covered 67 mm. When the number of comb teeth remained constant, $R_C$ increased and then leveled off as the stabbing depth increased, and the optimal range for the stabbing depth was 25–35 mm. When the stabbing depth remained unchanged, $R_C$ increased with the increase in the number of comb teeth and then tended to stabilize, with the optimal number of comb teeth being five. When the stabbing depth exceeded 35 mm, the elastic comb teeth, due to increased resistance from the soil, would skim over some of the weeds, thus affecting the weeding effectiveness.

The response surface of $R_S$ is concave, and from the color trend and steepness of the response surface, it can determine that the forward speed has a more significant effect on $R_S$ than the stabbing depth. The elastic comb is designed based on the appearance of the soybean plant, featuring a partial gap in the middle. This design reduces the likelihood of the comb teeth coming into contact with the soybean plant’s stems and leaves during the weeding operation, thereby minimizing the impact of the number of comb teeth. When the forward speed remains constant, $R_S$ gradually increases as the stabbing depth increases. Conversely, when the stabbing depth is constant, $R_S$ increases rapidly as the forward speed increases. It is observed that as the speed of the field management robot increases, there is a higher frequency of comb tooth seedling avoidance actions, leading to increased soil impact and resistance. This requires the comb teeth to possess greater stiffness and toughness. Additionally, there may be instances of jamming during the opening and closing of the seedling avoidance mechanism. Moreover, as the robot speed increases, the soybean recognition model’s recognition rate decreases, resulting in an increased rate of seedling injury. These findings align with the majority of current research on weeding machines. To mitigate the potential impact of forward speed on the seedling injury rate, the optimal forward speed range falls between 0.25 and 0.35 m/s.

Many weed control machines nowadays, despite incorporating image recognition technology for precise weeding, are expensive and not accessible to the general public. Clipper-type weeding components can quickly and accurately eliminate weeds, but they are only suitable for small grass with undeveloped root systems. Octopus-style weed removal components can partially remove interplant weeds; however, the outer cylindrical track of these weeding claws requires complex machining and high-precision assembly. Disk-shaped weed removal components are ineffective in removing weeds under hard soil conditions. Rotary hoe-style components are prone to entangling weeds, leading to the reseeding of weeds and crop coverage. Spring-tooth weed removal components, due to the
A large vibration amplitude when entering the soil, cause uneven soil disturbance, altering the original soil structure. The pulling-type weeding component relies on selective manual intervention to eliminate weeds. It involves significant labor intensity and is more suitable for short-duration and small-area weeding tasks.

In this study, the intermittent opening and closing of the comb teeth plate were used for weeding performance. It can remove inter-row weeds while cleaning intra-row weeds. The bottom of the elastic comb teeth is serrated, which can easily cut off the roots of weeds or hook out the soil surface. Moreover, the design of elastic comb teeth is based on the imitation of soybean appearance. This design effectively reduces the probability of the comb teeth coming into contact with the stems and leaves of soybean plants. Even if there is accidental contact with soybean plants, the elastic comb teeth will only cause the plants to deform slightly, significantly reducing the rate of seedling injury.

The field environment is complex, and there may be small stones and other debris around the soil, as well as differences in soil compaction. When working under different soil types and environmental conditions, the stability of the weeding mechanism and recognition system must be considered. The ground-mimicking wheel imitates the undulations of the ground to ensure that the weeding execution mechanism maintains a stable depth of entry into the soil, while also ensuring the stability of the detection range of the laser ranging sensor. The elastic comb teeth reciprocating soybean inter-row weeding device designed in this paper requires the weeding execution component to work deeply in the soil. In different soil types, the comb teeth may deform or break, and the position of the opening and closing of the comb teeth may also deviate. Multiple sets of comb teeth can be used for reinforcement to make them into a whole and enhance their rigidity. The shortcomings observed thus far will be further studied and addressed in future experiments.

6. Conclusions

1. A reciprocating soybean intra-row weeding device has been designed, which uses intermittent opening and closing of the comb teeth plates to avoid damaging seedlings. It can remove weeds between rows and some weeds within rows. A laser ranging sensor is used as the recognition tool, which has a simple principle and good performance.

2. The critical weeding components of the soybean intra-row weeding machine were analyzed and designed, and the safe range of soybean plants was determined to find the motion trajectory of the elastic comb teeth. The weeding rate is greatly improved while ensuring a low seedling injury rate. Weeding machines are combined with PLC programming and modeling for control, after the sensor detects the distance information of the plants. PLC can synchronize the normal weeding and seedling avoiding operations of the weeding mechanism through the soybean identification model.

3. Conducted via field weeding experiments, a quadratic regression universal center of rotation design test was conducted. The three-factor, three-level response surface analysis method was used to establish regression models for the weeding rate and seedling damage rate in relation to the stabbing depth, number of comb teeth, and forward speed. The experimental data were analyzed and optimized using the Design-Expert 8.0.5b software. It is found that the optimal operating performance of the weeding mechanism is achieved when the soil depth is 29.06 mm, the number of comb teeth is 5, and the forward speed is 0.31 m/s. Field performance tests demonstrate that the reciprocating soybean intra-row weeding device designed in this study meets the design requirements and can provide a reference for the design and optimization of soybean field mechanical weeding devices.

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