

## Article

# Design and Experiment of Row-Controlled Fertilizing–Weeding Machine for Rice Cultivation

Yangjie Shi <sup>1</sup>, Xiaobo Xi <sup>1,\*</sup> , Hao Gan <sup>2</sup> , Xiang Shan <sup>1</sup>, Yifu Zhang <sup>1</sup> , Hui Shen <sup>1</sup> and Ruihong Zhang <sup>1</sup>

<sup>1</sup> School of Mechanical Engineering, Yangzhou University, Yangzhou 225000, China; DX120180059@yzu.edu.cn (Y.S.); shanxiang@yzu.edu.cn (X.S.); zyfu@yzu.edu.cn (Y.Z.); hshen@yzu.edu.cn (H.S.); zhangrh@yzu.edu.cn (R.Z.)

<sup>2</sup> Department of Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, TN 37996, USA; hgan1@utk.edu

\* Correspondence: xbx@yzu.edu.cn

**Abstract:** Current approaches to topdressing and weeding operations for rice cultivation present several disadvantages, such as poor precision, low efficiency, serious environmental pollution, and so on. This paper presents a row-controlled fertilizing–weeding machine to improve the precision of fertilizing and weeding operations and to reduce the heavy pollution associated with rice cultivation. A proportional–integral–derivative algorithm was adopted to realize accurate fertilization control, and an automatic driving system for agricultural machinery based on BeiDou navigation was used for accurate row-controlled operation. Accuracy testing and field experiments were carried out. The results show that the fertilization control system can stabilize the speed to within 0.55 s of the desired speed with a standard deviation of around 0.32 r·min<sup>−1</sup>. The row-controlled operation ensures the lateral deviation is within ± 5 cm at operating speeds below 5 km·h<sup>−1</sup>. The high uniformity and accuracy of fertilization meet agronomic requirements and rice cultivation standards, and the weeding performance is acceptable at working speeds below 5 km·h<sup>−1</sup>.

**Keywords:** rice; fertilization; weeding; precision agriculture



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## 1. Introduction

Topdressing and weeding operations are repeatedly carried out throughout the rice cultivation process and have an important impact on rice yields. In the middle and lower reaches of the Yangtze River in China, the main topdressing method is mechanical sprinkling, which is highly efficient. However, it is difficult to achieve a uniform distribution of fertilizer, resulting in low fertilizer utilization rates [1,2]. The most widely used weeding methods are chemical-based. Plant protection machinery can achieve remarkable control of spraying operations. However, overuse of herbicides can lead to serious soil pollution and ecological damage [3,4].

Side deep fertilization and mechanical weeding technologies are used to ensure high fertilizer utilization rates and reduce chemical herbicide use [5]. By applying fertilizer to soil at a certain depth, it can be more easily absorbed by the root system, which can effectively increase fertilizer utilization rates by 15–20%; at the same time, yields can be increased by up to 20% [6,7]. Existing side deep fertilization devices exhibit poor performance, which is mainly reflected in low fertilization uniformity, unstable operation, and frequent clogging of fertilizer delivery pipelines [8,9]. In response to these problems, Wang et al. [10] adopted a spiral fertilizer discharge wheel to improve fertilization uniformity of a side deep fertilizing device. The coefficient of variation of fertilization stability was less than 7.8%. Shan Zeng et al. [11] and Kim et al. [12] designed pneumatic conveying systems suitable for granular fertilizer that improve the uniformity of fertilizer distribution and prevent blockage of the conveying pipe. In particular, Kim et al. showed that the application uniformity (coefficient of variation) in both the transverse and the longitudinal directions

were in the range of 11.2–13.1 and 2.9–15.3%, respectively. Moreover, the application accuracy ranged from 81.9–97.4% for the working speed range of the device. Yu et al. [13] designed a controller for variable-rate application of granular fertilizer, which adjusts the amount of fertilizer based on working speed and improves stability. The response time of the controller (time to reach a steady application rate when the application rate is suddenly changed) ranged from 1.5 to 3.0 s, which was considered acceptable.

Mechanical weeding is an environmentally friendly weeding technology and can be implemented using various approaches, including ploughing, harrowing, and intertillaging. These methods can eliminate the use of chemical herbicides and therefore, protect the ecological environment [14,15]. However, ensuring effective weeding while avoiding mechanical damage to rice seedlings remains a challenge [16]. Perez-Ruiz et al. [17] proposed a fully automatic intra-row mechanical weed knife path control system for transplanted row crops. The system uses a real-time kinematics (RTK) global positioning system (GPS) to automatically detect crop planting geolocations and to control the path of pairs of intra-row weed knives travelling between crop plants along the row centerline. Field trial results show that, on average, the size of the close-to-crop zone can be maintained within  $\pm 0.5$  cm of the target size with a standard deviation of 0.94 cm at  $0.8 \text{ km}\cdot\text{h}^{-1}$  and 1.39 cm at  $1.6 \text{ km}\cdot\text{h}^{-1}$ . Liu et al. [18] proposed a deep learning-based method for bending diagnosis of seedling line and guidance line extraction, which was shown to effectively prevent damage to seedlings caused by weeding machine components. Chen et al. [19] designed a hydraulic control system based on linear active disturbance rejection to prevent damage to seedlings caused by weeding components in paddy fields. The average seedling injury rate with the alignment control system was 3.9%. Wang et al. [20] designed a 3SCJ-1 type weeding machine that uses new weeding components for weed management in transplanted organic rice. The average weeding rate was 78.02%.

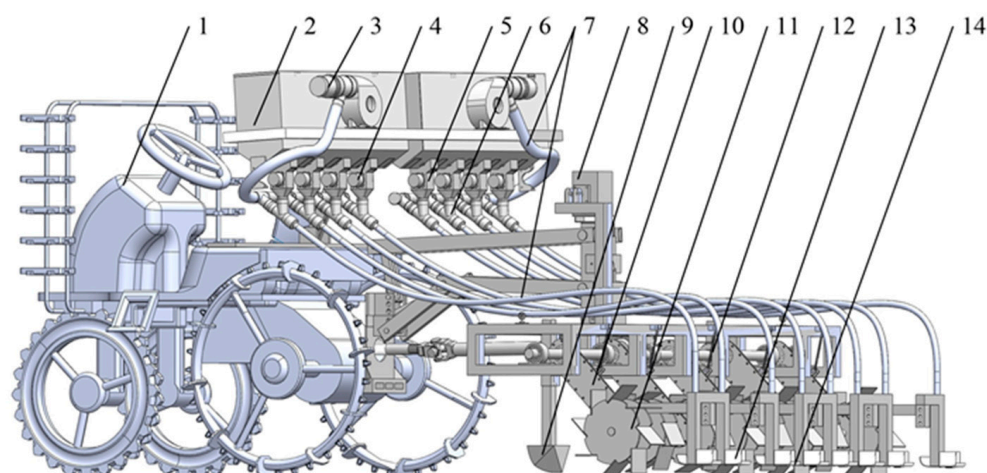
Although the above-mentioned approaches solve several common problems associated with fertilizing and weeding operations, they are only optimized for separately carrying out fertilizing or weeding operations. However, often only certain aspects of fertilizing or weeding operation are optimized, and from the agronomic point of view, combining these two operations to improve the efficiency has not been considered. This paper presents a row-controlled fertilizing–weeding (RFW) machine designed to meet the agronomic requirements of rice cultivation. The machine is capable of simultaneously performing fertilization and weeding operations and realizing row-controlled operation. An automatic driving system for agricultural machinery developed by our research group and based on China’s BeiDou navigation system is adopted to improve the efficiency and quality of both the fertilizing and weeding operations. An experimental study was carried out to assess the performance of the prototype. The results provide a theoretical basis, as well as a reference, for further research on combined fertilization, and weeding technologies for rice cultivation.

## 2. Materials and Methods

### 2.1. The Design of the RFW Machine

#### 2.1.1. Overall Structure

The RFW machine consists of a fertilizer box, fan, motor, fertilizer distribution apparatus, air–fertilizer mixing chamber, pipe, height adjustment device, furrower, gearbox, weeding wheel, spring, fertilizer tank, and depth-limiting plate. The machine is connected to the tractor body via the suspension frame. The overall structure of the RFW machine is shown in Figure 1. Technical details are listed in Table 1.



**Figure 1.** Overall structure of RFW machine. 1. Tractor; 2. Fertilizer box; 3. Fan; 4. Motor; 5. Fertilizer apparatus; 6. Air–fertilizer mixing chamber; 7. Pipe; 8. Height adjustment device; 9. Furrower; 10. Chain transmission box; 11. Weeding wheel; 12. Limiter spring; 13. Fertilizer tank; 14. Depth-limiting plate.

**Table 1.** Technical specifications of RFW machine.

Project	Parameter
Working width	2.5 m
Number of operation lines	8
Fertilizer box volume	350 L
Working speed	0–6 km h <sup>−1</sup>
Fan model	SEAFLO SFBB1-320-02
Type of fertilizer apparatus	Grooved wheel fertilizer apparatus
Motor model	GPG-05SC

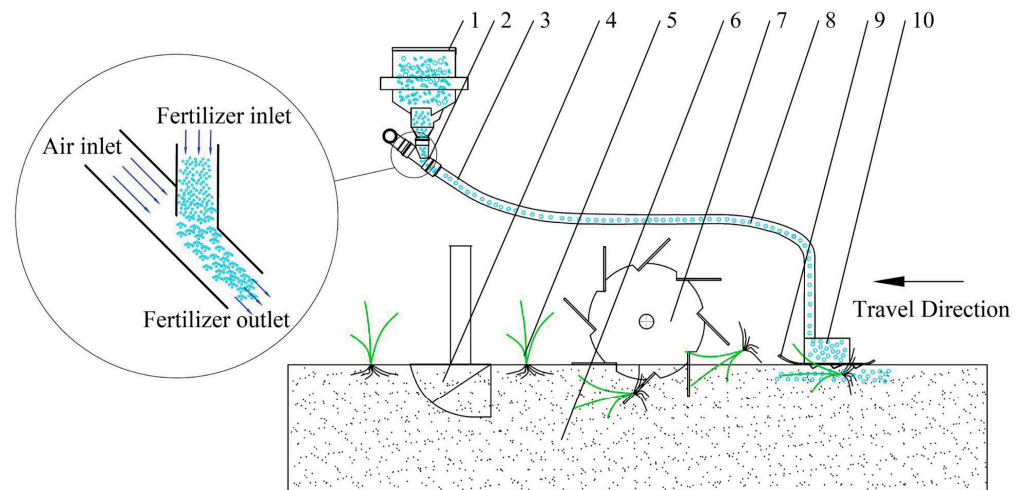
A pneumatic conveying method was adopted. Power is provided by the fan to convey the fertilizer. The rotation speed of the fertilizer apparatus is controlled by the motor speed, which therefore controls the amount of fertilizer dispensed. The height adjustment device adjusts the height of the machine relative to the ground, allowing the RFW machine to move easily through the field. The gearbox transfers the output power of the tractor to the weeding wheel, which then rotates. The furrower is used to trim ditches and plays a role in removing weeds between ditches. The depth-limiting plate and spring control the depth of the weeding wheel in the soil.

Fertilizer is discharged from the fertilizer tank through a square hole in the center of the depth-limiting plate. The RFW machine is equipped with an automatic driving system for agricultural machinery based on China’s BeiDou navigation system, which improves the accuracy of the row-controlled operation and ensures the weeding wheel stays between crop rows [21].

### 2.1.2. Working Principle

As shown in Figure 2, during the weeding operation, the weeding wheels plough shallow soil to dig out or bury weeds under the soil, destroying the root growth environment of the weeds. During the fertilizing operation, fertilizer particles are fed into the air–fertilizer mixing chamber under the action of the motor, then mixed with the high-speed air flow produced by the fan. The fertilizer particles enter the fertilizer tank through the pipe due to the combined action of drag forces generated by the air flow and gravity, and are finally discharged through the square hole in the center of the depth-limiting plate. The fertilizer particles fall into the soil immediately after it has been ploughed by the weeding wheel and are concentrated in the middle of the seedling row, thus realizing deep side fertiliza-

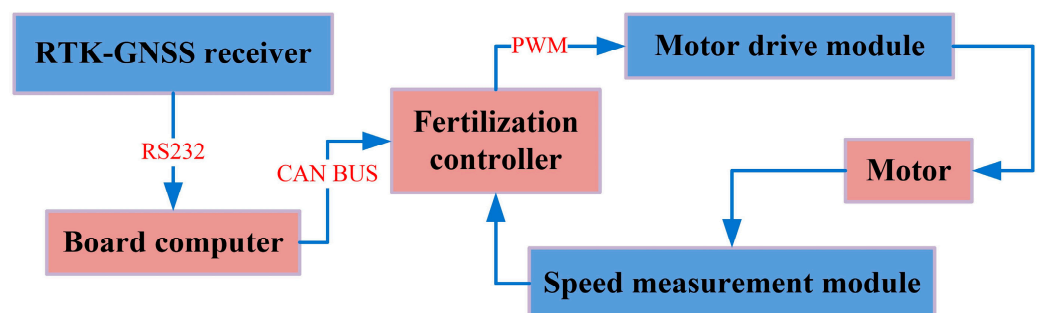
tion. The angle of the steering wheel is constantly adjusted during the row-controlled fertilizing and weeding operations, which effectively improves the efficiency and quality of both operations.



**Figure 2.** Working principle of RFW machine. 1. Fertilizer box; 2. Air–fertilizer mixing chamber; 3. Pipe; 4. Furrower; 5. Weeds; 6. Soil; 7. Weeding wheel; 8. Fertilizer; 9. Depth-limiting plate; 10. Fertilizer tank.

### 2.1.3. Control System

The fertilization control system was designed to improve the uniformity and accuracy of fertilization. The system uses a proportional–integral–derivative (PID) algorithm to achieve closed-loop control of the motor speed. The working principle of the system is shown in Figure 3. First, an RTK-based global navigation satellite system (GNSS) receiver monitors the working speed of the machine in real time and transmits the speed signal to an onboard computer. The desired motor speed is calculated by the computer based on the desired amount of fertilizer and machine parameters, then the desired speed is transmitted to the fertilization controller. The controller generates a pulse-width-modulated (PWM) signal, which is regulated by the PID controller, and the signal is sent to the motor drive module. The motor speed is controlled by changing the output voltage. At the same time, the speed measurement module feeds the actual working speed back to the controller, which alters the duty cycle of the PWM signal based on the above feedback, thereby realizing real-time control of the motor speed and precision fertilization.



**Figure 3.** Principle of fertilization control system.

Based on the desired amount of fertilizer, the relationship between the desired motor speed and working speed should meet the following requirements:

$$\begin{cases} dS(t) = \frac{w}{600} V_G(t) dt \\ dM_0(t) = M_0 dS(t) \\ dM_0(t) = nqN_0(t) dt \end{cases} \quad (1)$$

where  $S(t)$  is the corresponding operation area at time  $t$ , ha;  $M_0(t)$  is the desired amount of fertilizer per area corresponding to time  $t$ , kg·ha<sup>-1</sup>;  $N_0(t)$  is the desired motor speed at time  $t$ , r·min<sup>-1</sup>;  $V_G(t)$  is the actual working speed at time  $t$ , km·h<sup>-1</sup>;  $w$  is the working width, m;  $M_0$  is the desired amount of fertilizer per unit area, kg·ha<sup>-1</sup>;  $n$  is the number of fertilizer apparatuses; and  $q$  is the amount of fertilizer applied by the fertilizer apparatus during a single turn, kg.

The machine parameters can be used to obtain the control function for the desired motor speed as follows:

$$N_0(t) = \frac{5V_G(t)M_0}{192} \quad (2)$$

To achieve optimal control, it is necessary to adjust the PID controller parameters [22]. After repeated tests and tuning, the PID control law was obtained as:

$$U(t) = 278.9err(t) + 159 \int err(t)dt + 0.03 \frac{derr(t)}{dt} \quad (3)$$

where  $U(t)$  is the output of the PID controller and  $err(t)$  is the deviation between the desired speed and actual speed.

Proper function of the row-controlled system relies on the automatic driving system for agricultural machinery based on BeiDou navigation. The operating principle of the row-controlled system is shown in Figure 4. First, the system reads the original path data for rice seeding and planting, which is used as a baseline for planning the desired path. The lateral and heading deviation are obtained by comparing the real-time position and heading information of the RFW machine with the desired path. Then, the theoretical rotation angle is calculated according to the deviations of the two desired values, within a predetermined error value limit. The actual controlled rotation angle is calculated based on the feedback signal from the rotation angle measuring device [23]. The motor drives the electronically controlled steering wheel, and the rotation angle is controlled to realize accurate row-controlled operation.

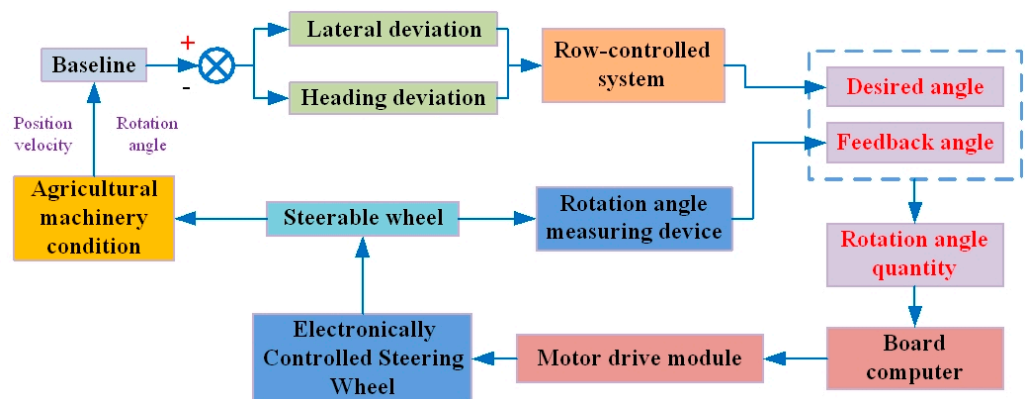


Figure 4. Principle of row-controlled system.

## 2.2. Accuracy Testing of Control System

### 2.2.1. Analysis of Response Characteristics of Fertilization Control System

To ensure fertilization uniformity in the longitudinal direction, the fertilization control system should quickly respond to changes in the working speed to ensure the motor speed stabilizes around the desired speed within a relatively short period of time. The motor speed was tested and analyzed under load conditions. In the experiment, the motor speed was programmed to change every 15 s in the range 10–30 r·min<sup>-1</sup>, and the motor speed data were recorded every 100 ms by the speed measurement module. Finally, the variation of motor speed with load was obtained.

### 2.2.2. Analysis of Row-Controlled System Accuracy

The purpose of row-controlled operation is to reduce mechanical damage to rice seedlings caused by weeding components during the weeding operation. Deviation of the row-controlled operation must be controlled within a certain range. Deviation is mainly due to system error, vibration of the machine, and suspension deflection. Moreover, the operating speed will also influence the amount of deviation caused by these sources. Thus, the influence of the operating speed of the machine on the deviation of the row-controlled operation must be analyzed to determine the appropriate working speed range.

A field experiment was carried out on 28 June 2020 in an experimental field of Jinyun Agricultural Science and Technology Development Co., Ltd., Jiangdu District, Yangzhou City, Jiangsu Province, China (119.512° E, 32.562° N). During the test, the working speed of the machine was set to 3, 4, 5, and 6 km·h<sup>-1</sup> and the machine travelled 150 m along the desired path. The actual working path was monitored by a high-precision satellite receiver installed on the longitudinal center line of the machine. Thirty monitoring points were selected along the path. Afterwards, the lateral deviation was calculated. The lateral deviation was taken as the offset distance between the actual working path and the desired path. As the absolute lateral deviation increases, the accuracy of the row-controlled operation decreases.

## 2.3. Field Experiment

The experiment was carried out according to NY/T1003-2006, Technical Specification of Quality Evaluation for Fertilizing Machinery [24]. Rice cultivation operations were performed by machines equipped with an automatic driving system for agricultural machinery based on BeiDou navigation. The row spacing was 0.25 m, the rice seedling height was in the range of 0.2 to 0.3 m, and the weed height was in the range of 0.1 to 0.2 m. Urea with a particle size range of 0.85 to 2.8 mm was selected as the fertilizer.

### 2.3.1. Fertilization Uniformity

The fertilization uniformity obtained using the proposed fertilization control system was measured under static conditions. Consistency in the amount of fertilizer applied to each row was analyzed using the coefficient of variation (CV). A value of less than 13% meets the technical requirements (NY/T 1003-2006). The eight fertilizer outlets were labelled as 1–4 on the left side and 5–8 on the right side of the machine. The *t*-tests were performed to verify the fertilization uniformity on each side based on data obtained from fertilizer outlets on the left and right sides of the machine. The coefficient of variation of the amount of fertilizer in each row was calculated as:

$$CV = \frac{\sqrt{\sum_{i=1}^n \frac{(x_i - \bar{x})^2}{n-1}}}{\bar{x}} \cdot 100\% \quad (4)$$

where  $x_i$  is the amount of fertilizer in each row,  $\bar{x}$  is the average amount of fertilizer in each row,  $g$ ; and  $n$  is the number of test rows (i.e., number of fertilizer outlets).

In the experiment, the motor speed was set to 10, 15, 20, 25, or 30 r·min<sup>-1</sup>. The number of test rows was 8 and the test time was 5 min. Fertilizer dispensed from each outlet was

collected in 8 separate buckets. At the end of each test, the fertilizer in each bucket was weighed and recorded. The test was repeated three times at each speed and the average values were calculated. The coefficient of variation of the amount of fertilizer in each row was determined using Equation (4). The total amount of fertilizer dispensed from each fertilizer outlet was measured and independent sample *t*-tests were performed using the average values. The significance level was set to  $\alpha = 0.05$ .

### 2.3.2. Fertilization Accuracy

The deviation of fertilization rate ( $\gamma_s$ ) was used to evaluate fertilization accuracy. Deviation of the total amount of fertilizer refers to the ratio of the absolute value of the difference between the actual amount and the desired amount, expressed as:

$$\gamma_s = \frac{\left| \frac{10,000(W_b - W_a)}{S} - F \right|}{F} \cdot 100\% \quad (5)$$

where  $W_b$  is the mass of fertilizer added to the fertilizer box at the start of the experiment, kg;  $W_a$  is the mass of residual fertilizer in the fertilizer box at the end of the experiment, kg;  $S$  is the operation area,  $m^2$ ; and  $F$  is the desired amount of fertilizer,  $kg \cdot ha^{-1}$ .

The test plot was divided into ten areas ( $2.5 \text{ m} \times 100 \text{ m}$ ), the working speed was set to  $3 \text{ km} \cdot h^{-1}$ , and the desired amount of fertilizer was set as 150, 250, or  $350 \text{ kg} \cdot ha^{-1}$ , respectively. The total mass of fertilizer in the fertilizer box was weighed before and after the experiment, then the deviation of the total amount of fertilizer in the test area was calculated using Equation (5). The deviation of the total amount of fertilizer should be below 15%.

### 2.3.3. Weeding Performance

Weeding performance is mainly reflected in the removal effect of weeds per unit area and the degree of mechanical damage to rice seedlings. Here, weeding rate ( $\lambda$ ) and seedling injury rate per unit area ( $\eta$ ) were used as evaluation indexes [25]. The test plot was divided into four  $2.5 \text{ m} \times 100 \text{ m}$  areas, and five  $2.5 \text{ m} \times 1 \text{ m}$  areas within these four areas were selected for testing. The working speeds were set as 3, 4, 5, and  $6 \text{ km} \cdot h^{-1}$ , respectively. The weeding rate and seedling injury rate were calculated using the following formulas:

$$\lambda = \frac{Q_b - Q_a}{Q_b} \cdot 100\% \quad (6)$$

where  $\lambda$  is the weeding rate, %;  $Q_b$  is the total number of weeds in the test area before weeding; and  $Q_a$  is the total number of weeds in the test area after weeding.

$$\eta = \frac{U_b}{U_a} \cdot 100\% \quad (7)$$

where  $\eta$  is the seedling injury rate, %;  $U_b$  is the total number of damaged rice seedlings in the test area (stem broken or bent and epidermis damaged); and  $U_a$  is the total number of rice seedlings in the test area.

Each test was repeated three times at each speed and the average values were calculated. The evaluation index was estimated for the overall area based on those of the smaller test areas. According to the rice weeding requirements, the weeding rate should be above 75% and the injury rate should be below 5%. The weeding rate and injured seedling rate were statistically analyzed using analysis of variance (ANOVA), with a significance level of  $\alpha = 0.05$ .

### 3. Results and Discussion

#### 3.1. Analysis of Control System Accuracy

##### 3.1.1. Response Characteristics of Fertilization Control System

Figure 5 shows the response of the actual motor speed to changes in the target speed. The response times of the system to achieve a stable speed close to the target speed were 0.55, 0.31, 0.32, 0.41, and 0.35 s. Thereafter, the actual motor speed tended to fluctuate up and down around the desired speed within an acceptable range. Standard deviations of the actual speed after stabilization were 0.26, 0.32, 0.21, 0.14, and 0.21  $\text{r}\cdot\text{min}^{-1}$ . The response time of the system was 0.31–0.55 s, which was shorter than that of the controller designed by Yu et al. [13], which ranged from 1.5 to 3.0 s, while the standard deviations of the actual speed after stabilization were very close. Thus, the control accuracy of the system is high and stable control can be achieved.

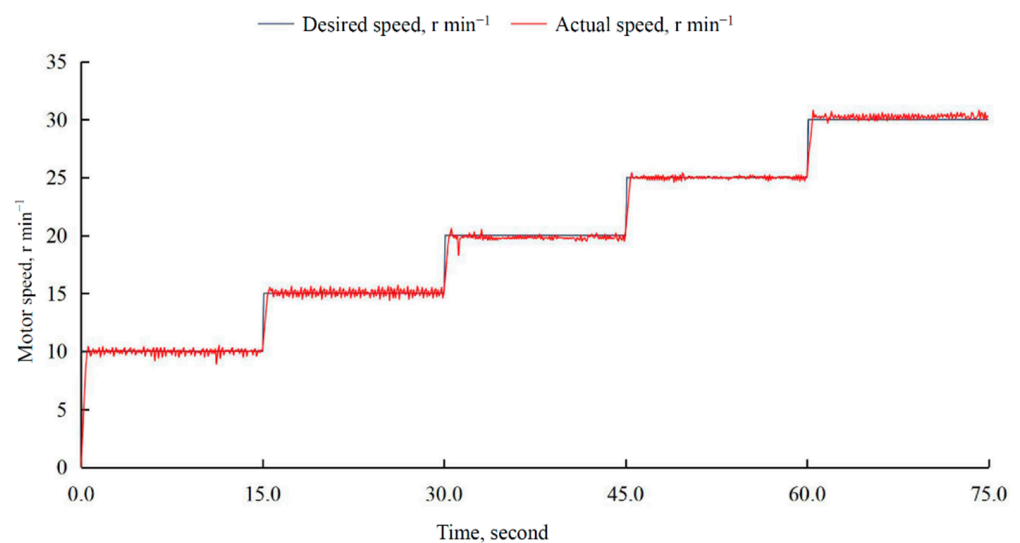


Figure 5. Desired speed versus actual motor speed.

##### 3.1.2. Row-Controlled System Accuracy

Figure 6 shows the lateral deviation of the row-controlled operation at different speeds. The lateral deviation increased with increasing motor speed. The ranges of lateral deviation were  $-3.15$ – $3.18$ ,  $-3.82$ – $4.13$ ,  $-5.32$ – $5.33$ , and  $-6.43$ – $5.76$  cm at working speeds of 3, 4, 5, and 6  $\text{km}\cdot\text{h}^{-1}$ , respectively. According to the rice cultivation requirements for the middle and lower reaches of the Yangtze River in China, the row spacing should be 25 cm. Based on the above results and technical specifications of the machine, a lateral deviation of  $\pm 5$  cm is considered acceptable. When the lateral deviation is too large, unstable movement of the lateral offset of the weeding wheel may damage seedling roots. To reduce the damage caused by the weeding wheel, the working speed should be controlled to below 5  $\text{km}\cdot\text{h}^{-1}$ .



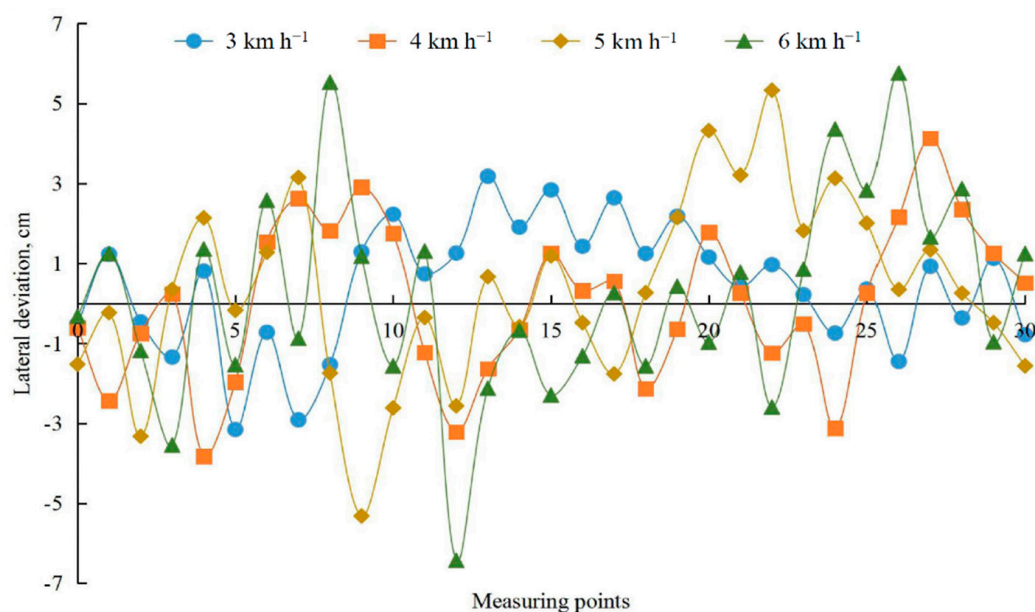


Figure 6. Lateral deviation of row-controlled operation at different speeds.

### 3.2. Results of Field Experiment

#### 3.2.1. Fertilizer Application Uniformity

Table 2 shows the amount of fertilizer applied in each row at different motor speeds. The CV of the amount of fertilizer in each row ranged from 1.14 to 2.50%, which meets the requirement of CV less than 13%. As the motor speed increased, the amount of fertilizer in each row increased linearly. At the same time, the CV of the amount of fertilizer in each row decreased, indicating the application uniformity among rows increased.

Table 2. Statistical analysis of consistency in the amount of fertilizer in each row.

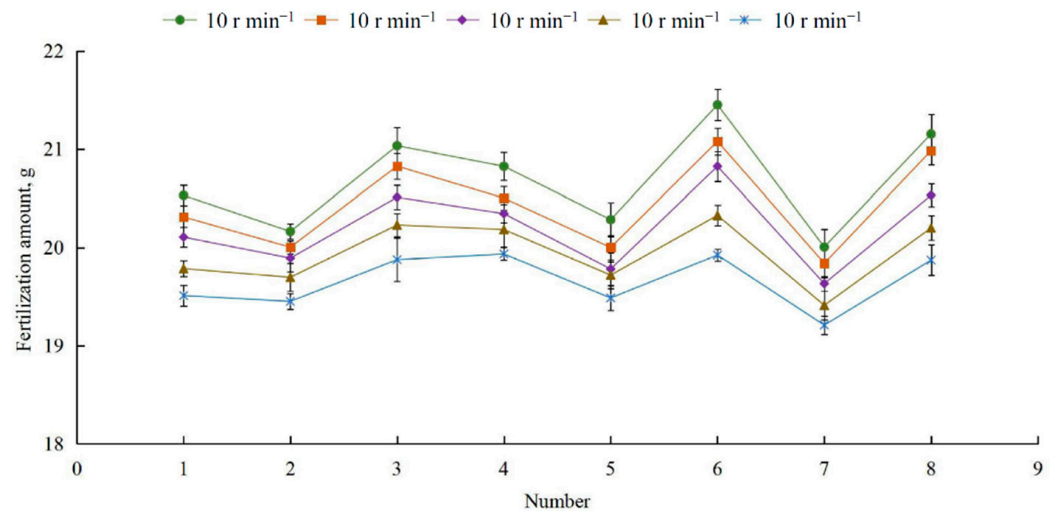
Speed (r·min <sup>-1</sup> )	Amount of Fertilizer (g)								CV (%)
	1	2	3	4	5	6	7	8	
10	1026.55	1008.25	1051.75	1041.25	1014.25	1072.61	1000.35	1057.75	2.50
15	1523.48	1500.38	1562.03	1537.73	1500.15	1580.93	1488.08	1573.80	2.35
20	2010.81	1989.42	2051.21	2034.63	1978.32	2082.51	1963.42	2053.23	2.06
25	2473.38	2462.25	2528.88	2523.13	2465.13	2541.13	2426.63	2525.13	1.66
30	2926.83	2917.95	2981.72	2990.41	2923.23	2988.75	2881.65	2980.95	1.41

Table 3 shows the results of an independent sample *t*-test for the average amount of fertilizer dispensed from outlets on the left and right sides of the machine. The corresponding *p* values for each speed show there is no significant difference in the amount of fertilizer dispensed from the left and right fertilizer outlets.

Table 3. Results of independent sample *t*-test for the average amount of fertilizer dispensed from the left and right fertilizer outlets.

Speed (r min <sup>-1</sup> )	t Stat	<i>p</i>
10	−0.22	0.83
15	−0.18	0.87
20	0.07	0.95
25	0.23	0.82
30	0.34	0.74

Figure 7 shows the amount of fertilizer applied during a single turn of the fertilizer apparatus at different motor speeds. At a constant motor speed, the amount of fertilizer fluctuates slightly. Overall, the amount of fertilizer was consistent, with a standard deviation of less than 0.52 g. The fluctuation is likely related to differences in the characteristics of different fertilizer distribution apparatuses. Nonetheless, as the speed increased, the amount of fertilizer tended to decrease.



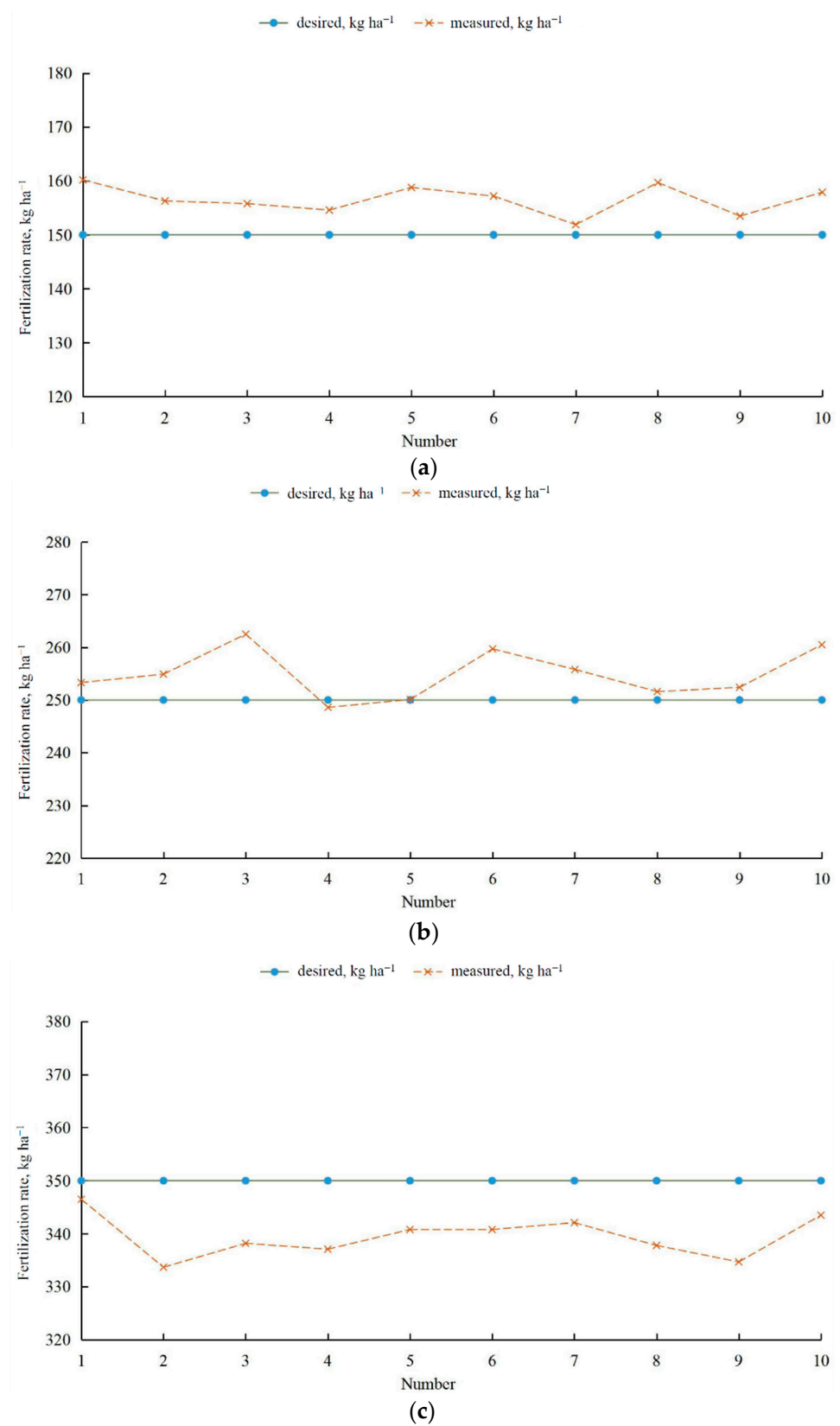
**Figure 7.** Amount of fertilizer applied during a single turn of the fertilizer distribution apparatus at different working speeds.

### 3.2.2. Fertilizer Application Accuracy

Figure 8 compares the desired and measured fertilization rates for three different target values. When the desired fertilization rate was  $150 \text{ kg}\cdot\text{ha}^{-1}$ , the measured fertilization rate was generally higher than the desired fertilization rate; whereas, when the desired fertilization rate was  $350 \text{ kg}\cdot\text{ha}^{-1}$ , the measured fertilization rate was generally lower. The reason for this may be that at a constant working speed, the motor speed must increase to increase the amount of fertilizer dispensed. However, as the motor speed increases, the amount of fertilizer applied by the fertilizer distribution apparatus during a single turn will decrease, leading to a decrease in fertilization rate, which is consistent with the results presented in Figure 7.

Table 4 shows the deviation between the desired and measured fertilization rates. When the desired fertilization rates were 150, 250, and  $350 \text{ kg}\cdot\text{ha}^{-1}$ , the deviation ranges of the actual fertilization rates were 1.27–6.80, 0.04–5.00, and 1.00–4.66%, respectively. The deviation of less than 15% meets the fertilization requirements and the application accuracy of the machine meets the design requirements.

Compared with the CV and deviation obtained by Wang et al. [10], Shan Zeng et al. [11] and Kim et al. [12], the change in the CV and deviation shows the same trend: the faster the motor speed is, the smaller the CV is. The larger the desired fertilization rate is, the smaller the deviation is. Under the same motor speed, the values of CV and deviation of this paper are smaller, e.g., the CV obtained by Kim et al. [12] were in the range of 11.2 to 13.1%, and the deviation ranged from 2.6 to 18.1%. It proves that the uniformity and accuracy of fertilizer application of the prototype are worthy of affirmation.



**Figure 8.** Desired versus measured fertilization rates for target values of (a) 150, (b) 250, and (c) 350 kg·ha<sup>-1</sup>.

**Table 4.** Deviation of measured fertilization rate from desired values.

Desired (kg·ha <sup>-1</sup> )	$\gamma_s$ (%)									
	1	2	3	4	5	6	7	8	9	10
150	6.80	4.20	3.87	3.07	5.87	4.80	1.27	6.47	2.33	5.27
250	1.32	1.96	5.00	0.56	0.04	3.88	2.32	0.64	0.96	4.20
350	1.00	4.66	3.37	3.69	2.63	2.63	2.26	3.49	4.37	1.86

### 3.2.3. Weeding Performance

Table 5 shows statistical data for weeding rate and seedling injury rate at different working speeds. In a working speed range of 3 to 6 km·h<sup>-1</sup>, the weeding rate was 78.3–83.1%, which meets the requirements of the rice weeding operation. Table 6 shows the ANOVA results for the variation in average weeding rate with working speed. The *p*-value was far less than 0.05, indicating that the working speed has a significant impact on the weeding rate. The weeding rate decreased with increasing working speed, suggesting that the weeding wheel is less effective at higher speeds. As the working speed of the machine increases, the slip rate of the weeding wheel also increases and the ploughing effect is reduced, which leads to a decrease in weeding rate.

**Table 5.** Weeding rate and seedling injury rate at different working speeds of the machine.

Speed (km·h <sup>-1</sup> )	3	4	5	6
Weeding rate (%)	83.1 ± 3.5	81.7 ± 1.7	79.8 ± 2.6	78.3 ± 2.1
Seedling injury rate (%)	3.2 ± 0.7	4.1 ± 0.5	5.6 ± 0.4	7.3 ± 0.9

**Table 6.** Analysis of variance results for influence of working speed on weeding rate.

Source	SS	df	MS	F	<i>p</i> -Value	F Crit
Between groups	39.31583	3	13.10528	103.4627	9.71E-07	4.066181
Within groups	1.013333	8	0.126667			
Total	40.32917	11				

In the working speed range of 3 to 6 km·h<sup>-1</sup>, the seedling injury rate was 3.2–7.3%. Table 7 shows the ANOVA results for the variation of seedling injury rate with working speed. The *p*-value is far less than 0.05, indicating that the working speed has a significant impact on seedling injury rate. The seedling injury rate increased with increasing working speed, which suggests that increasing the speed will reduce the accuracy of the row-controlled system, which is consistent with the results presented in Figure 6. Moreover, a seedling injury rate above 5% does not meet rice weeding operation requirements. To meet the requirements of the rice weeding operation in terms of weeding injury rate, the working speed must be below 5 km·h<sup>-1</sup>.

**Table 7.** Analysis of variance results for variation of seedling injury rate with working speed.

Source	SS	df	MS	F	<i>p</i> -Value	F Crit
Between groups	29.07	3	9.69	33.70435	6.9E-05	4.066181
Within groups	2.3	8	0.2875			
Total	31.37	11				

Regarding the existing technical solutions of mechanical weeding proposed by Chen et al. [19] and Wang et al. [20], both solutions can achieve a good weeding effect. Under the speed of 3 km·h<sup>-1</sup>, the weeding rate and seedling injury rate of the existing mechanical weeding

equipment can reach 78.02% and 3.9%, respectively. At this speed, the weeding rate and seedling injury rate of the prototype were 83.1% and 3.2%, respectively. The performance of the prototype is slightly better than the above two kinds of equipment, but the gap is not big.

Figure 9 shows the weeding effect of the machine. From a comparison of the number of weeds and the damage to rice seedlings in the operation area and non-operation area, no obvious weed residues were observed in the operation area. The damage to rice seedlings was relatively low, which meets the requirements of the rice weeding operation and demonstrates good performance of the machine.



**Figure 9.** Results of weeding and fertilizing operations using an RFW machine.

### 3.3. Limitations

The findings of this study have to be seen in light of some limitations. First, constrained by the work principle of the row-controlled system, the machine is only applicable to paddy fields which were planted by using the automatic driving system for agricultural machinery based on BeiDou navigation. Of course, with the increasing popularity of the automatic driving system for agricultural machinery, the limitation will be greatly reduced. Secondly, due to the fact that there is no similar machine on the market, this paper only evaluates the performance of the machine according to the existing standards and existing technical solutions, and does not carry out comparative tests. At last, the scope of the field experiments are not substantial enough to understand the adaptability of the machine to different regions and soil environments. The adaptability of the device should be verified in the future.

### 4. Conclusions

To improve the efficiency and quality of rice fertilization and weeding operations and to reduce agricultural non-point source pollution, a row-controlled fertilizing–weeding machine was developed. Accurate fertilization control and row-controlled operation were

realized using a PID algorithm and automatic driving system for agricultural machinery based on BeiDou navigation. The fertilization control system can stabilize the speed of the machine to within 0.55 s of the desired speed with a standard deviation of around  $0.32 \text{ r} \cdot \text{min}^{-1}$ . The row-controlled operation ensures a lateral deviation of  $\pm 5 \text{ cm}$  at operating speeds below  $5 \text{ km} \cdot \text{h}^{-1}$ , which meets the operational accuracy requirements of rice cultivation. The field test results show that the uniformity and accuracy of fertilization of the RFW machine are high. The coefficient of variation of the amount of fertilizer in each row ranged from 1.14 to 2.50%, with corresponding deviation in corresponding fertilization rates below 6.80%. The proposed system meets all requirements of the Chinese Technical Specification of Quality Evaluation for Fertilizing Machinery (NY/T1003-2006). In the working speed range of 3 to  $6 \text{ km} \cdot \text{h}^{-1}$ , the weeding rate was 78.3–83.1% and the seedling injury rate was 3.2–7.3%. Therefore, working speeds below  $5 \text{ km} \cdot \text{h}^{-1}$  are acceptable for rice weeding operations.

In terms of operation efficiency, the machine integrates the fertilization and weeding operations to eliminate single-step operations, and greatly improves the operating efficiency. In terms of operation quality, precision fertilization and row-controlled operation are achieved using a PID controller and BeiDou navigation system, which were shown to improve the uniformity and accuracy of fertilization and effectively reduce the seedling injury rate while ensuring the desired weeding effect. In terms of environmental protection, side deep fertilization effectively increases fertilizer utilization rates and reduces runoff losses from the fertilizer. In addition, mechanical weeding avoids the use of herbicides, which can significantly reduce the ecological impact of rice cultivation on the farmland environment. Further research on the RFW machine will be of great significance in the field of rice cultivation.

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