Variable rate fertilization system with adjustable active feed-roll length

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Abstract: This paper presented a novel variable rate fertilization system based on the method of adjusting the active feed-roll length of a fluted roller. The feasibility of this method was discussed using analysis of the fluted roller model. One seed drill produced by Kuhn Company (France), which could sow and fertilize simultaneously, was used as a test platform to implement the mechanical structure of variable rate fertilization. The design methods for the variable rate fertilization mechanical structure and actuator were introduced in detail. A low-cost and stable embedded support decision subsystem and corresponding software were developed. The support decision subsystem is based on grid management. Each grid field cell contains information about corresponding spatial position and fertilizer application rate. A SpatiaLite database was employed to solve the spatial location search and spatial data query. Experiments were conducted to evaluate the fertilization uniformity and dynamic response time. The average value of coefficient of variation is 8.4% in five different active feed-roll lengths which reflects good uniformity. The dynamic response times for the adjustment of variable rate fertilization system from 204 kg/hm^2 to 319 kg/hm^2 and 319 kg/hm^2 to 204 kg/hm^2 are about 4.2 s. The results suggest that the variable rate fertilization system performs well in dynamic adjustment and stability.

Keywords: precision agriculture, variable rate fertilization, fluted roller, active feed-roll length, servo drive, embedded system
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1 Introduction

Precision agriculture aims to improve yield, quality and benefits for famers by optimizing agriculture inputs[1,2]. Avoiding excessive application of fertilizer is one of the important outcomes of precision agriculture. The variable rate fertilization (VRF) technology can improve fertilizer utilization efficiency, and reduce environmental impact[3]. The intention of VRF is to apply specific and precise fertilizer at different sites to satisfy site-specific management requirements[4-6]. In modern large-scale farming, most types of fertilizer are granular and should be applied in soil at a certain depth. A fluted roller fertilizer distributor used as a traditional fertilizer feeder can eliminate the influence of surface roughness, box stock and travelling speed. The fluted roller performs well when applying granular fertilizer. The amount of fertilizer is metered by its flutes. With the advantages of simple structure and uniformly applying fertilizer, the fluted roller has been widely adopted within the mechanical design of modern fertilizer spreaders[7]. However, most modern fertilizer spreaders are designed as uniform application machines. It is meaningful to develop a VRF system that uses the fluted roller fertilizer distributor for the modern fertilizer spreader. Generally, the VRF for fluted roller is implemented through controlling the rotational speed of

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the fluted roller directly[8,9]. However, this method has some inevitable defects, for example, complicated mechanical structure and longer response time. To overcome these disadvantages, this paper presents a new control method of adjusting the active feed-roll length of the fluted roller. The active feed-roll length is the workable length of a fluted roller. A movable baffle covers a section length of the fluted roller to stop fertilizer discharge and leaves the rest of the workable length functioning as normal. The linear relationship between the fertilizer application rate and the active feed-roll length was discussed in this paper. A servo-driven actuator was used to realize precise control over the active feed-roll length.

The fertilization support decision subsystem, another key component, determines the operating cost of VRF system. It is necessary to design a low-cost and reliable support decision subsystem. Ess et al.[10] summarized two types of VRF system: map-based and sensor-based. The map-based method, implemented with a fertilizer prescription map, is commonly adopted in VRF systems because of its easy application. Yuan et al.[11] developed a GPRS network supported VRF system which stores the fertilizer prescription map in a remote server. The GPRS network transmission delay can be disastrous for the system. Moreover, there is no GPRS signal in most remote farming areas. The workflow of the VRF system relies on the support of a remote server which makes the cost of hardware very expensive. All of these issues make the system difficult to be widely used. In this paper, an embedded VRF support decision subsystem based on mobile geographic information system (GIS) is developed. The fertilization data is stored in an offline SpatiaLite database. The corresponding software is developed for Android operating system (OS). A series of experiments were conducted to evaluate the performance of the VRF system. The objective of this study is to introduce a new design method for a VRF system. The control method based on adjusting the active feed-roll length must precisely regulate fertilizer application rate. We give the detailed design method for the VRF actuator in this paper. To make the VRF system promotable and viable, the embedded VRF support decision subsystem which we developed is low-cost and stable.

2 Materials and methods

2.1 Model analysis of fluted roller

The structure of a fluted roller fertilizer distributor is shown in Figure 1. The fluted roller (Figures 1a and 1b) is wrapped around the outer cover. The fertilizer in the hopper is constantly being poured into the fluted roller fertilizer distributor from the top entrance as a result of the gravity and mechanical vibration. The fertilizer application rate is metered by the active feed-roller length (Figure 1c) of the fluted roller. The measurable fertilizer is transported into the soil via pipeline (Figure 1d).

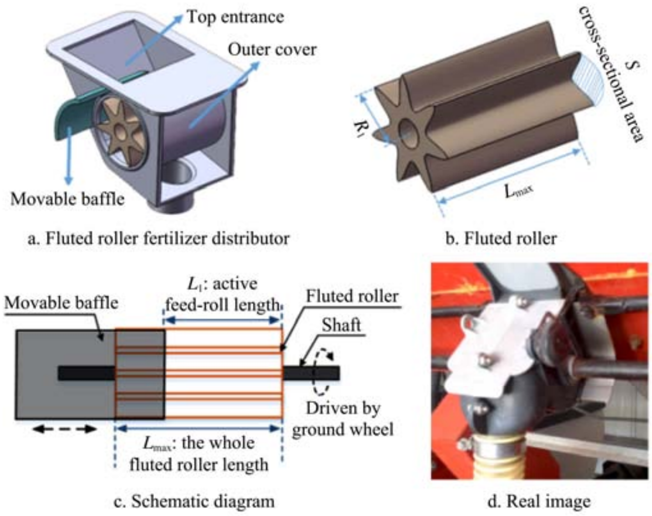


Figure 1 Structure of a fluted roller fertilizer distributor

The fertilizer application rate of the fluted roller fertilizer distributor is expressed as q (kg/r), which is the weight of fertilizer discharged per revolution. The q consists of q_1 and q_2, q_1 is the main part of fertilizer amount discharged by the metering flutes; q_2 is the extra fertilizer amount needed because of the gap between the fluted roller and the outer cover. The calculations of q, q_1 and q_2 are given in Equations (1) - (3).

$$q = q_1 + q_2 \tag{1}$$

$$q_1 = \rho \alpha z s L_1 \tag{2}$$

$$q_2 = \rho \lambda 2\pi R_1 L_1 \tag{3}$$

where, α is the fullness coefficient of fertilizer in the fluted roller; λ is the fullness coefficient of fertilizer in the gap; z is the total number of flutes in the fluted roller; ρ is the volume-weight of fertilizer, kg/m^3; s is the cross-sectional area of one flute, m^2; R_1 is the radius of the fluted roller, m; L_1 is the active feed-roll length of the fluted roller, m.

When the fluted roller rotates, the fertilizer application rate M (kg) is expressed as follows:

$$M = n_1 \cdot q \tag{4}$$

where, n_1 denotes the number of turns of the fluted roller.

The fertilizer application area is S (m^2), and it can be represented as follows:

$$S = n_2 2\pi R_2 L_2 \tag{5}$$

where, n_2 represents the number of turns of the ground wheel; R_2 denotes the radius of ground wheel, m; L_2 is the working width of the fluted roller (row spacing), m.

The fertilizer application rate in unit area ΔM (kg/m^2) can be expressed as:

$$\Delta M = \frac{M}{S} = \rho \cdot \frac{\alpha z s + 2\pi\lambda R_1}{2\pi R_2 L_2} \cdot \frac{n_1}{n_2} \cdot L_1 \tag{6}$$

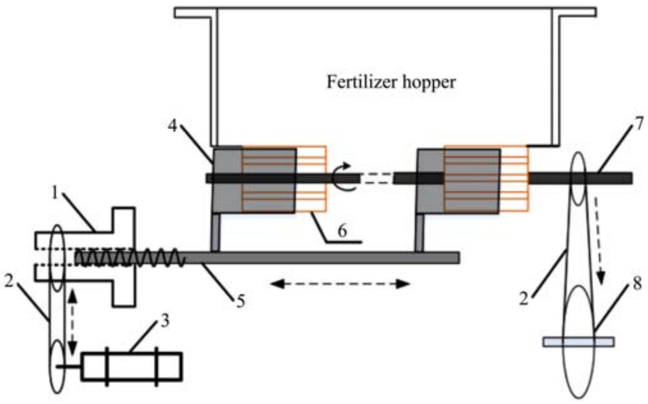
The parameters ρ, α, z, s, λ, R_1, R_2 and L_2 are inherent characteristics of a fertilizer spreader. The linear-relationship between ΔM and n_1/n_2 or L_1 is shown in Equation (6). Consequently, ΔM could be adjusted in two ways. The first way is to adjust n_1/n_2 with a fixed L_1. This method was commonly adopted in previous VRF systems[8,9]. Based on this approach, the fertilizer application rate is customized by changing the rotational speed ratio (drive ratio) between the fluted roller and the ground wheel of the fertilizer spreader. Electronic controlled variable transmission (CVT) or an independent high power motor are always used to achieve mechanical control for this method. However, the mechanical structure of CVT is complicated and the cost of mechanism reconstruction is expensive. The independent motor needs high-power for driving the shaft of fluted roller. It is difficult to ensure operational smoothness of the high-power motor, so it cannot guarantee high precision of fertilizer application. The real-time revolution speed of the fluted roller and ground wheel must be measured and recorded simultaneously, which may cause more measuring errors for the VRF control system. The second way is to adjust L_1 with a fixed n_1/n_2 which is adopted in this paper. Different from the approach mentioned above, this method as a new scheme adjusts the active feed-roll length of the fluted roller to realize VRF with a fixed drive ratio. The rotation of the fluted roller is driven by the ground wheel directly so that both have synchronous motion. The biggest advantage of this method is the single control variable (the active feed-roll length) which can reduce adjustment error. This means it can reach a higher precision fertilizer application rate and a quicker response time.

2.2 Implementation of VRF actuator

2.2.1 Design of VRF mechanical structure and the servo-driven actuator

The drill (Model Maxima 2, Kuhn Company, France) with seven fluted rollers is chosen as the VRF test platform in this paper. For this drill, the sowing and fertilizing can work simultaneously, and this is a common practice for corn and soybean planting. The seven fluted rollers are coaxial and the rotations are synchronized by a ground wheel. Each fluted roller corresponds to one row in practical field fertilization. This drill can be set to a fixed fertilizer application rate manually before field fertilizer application occurs. However, the fertilizer application rate cannot be adjusted in real time according to within-field variability. Therefore, an improved mechanical structure for cooperation with the servo-driven actuator was designed to achieve variable rate control for this drill in real time. The schematic of VRF mechanical structural design is shown in Figure 2a.

The whole VRF control system contains two main parts: (a) servo-driven actuator; (b) embedded VRF support decision subsystem. The servo-driven actuator includes the servo controller and servo motor. The servo controller receives the precise number of revolutions from the embedded VRF support decision subsystem and then drives the servo motor using precise current signals. The cross lead screw nut rotates synchronously with the chain wheel. So the number of revolutions is converted into horizontal displacements of the feed adjusting lever by using the cross lead screw nut. The moveable baffle for adjusting active feed-roll length is fixed on the feed adjusting lever. When the feed adjusting lever moves a certain horizontal distance, the baffle will move the same length simultaneously. So the goal of adjusting the fertilizer application rate accurately can be achieved by precisely controlling the servo motor.



a. Schematic diagram

b. Installation diagram

1. Cross lead screw nut 2. Chain wheel 3. Servo motor 4. Movable baffle 5. Feed adjusting lever 6. Fluted roller 7. Drive shaft 8. Ground wheel

Figure 2 The VRF mechanical structure

In this paper, the VRF support decision subsystem is based on grid management, which is implemented with a prescription map generated by dividing fields into grid cells which have fertilization rate data. The major application of the field grid cell aims to provide unique identification and corresponding fertilization data. The field grid size is set to 19 m×19 m which represents one second in latitude where the field is located (Northeast China). The time of a fertilizer spreader passing a field grid cell t (s) is expressed as follows:

$$t = w / v \tag{7}$$

where, w denotes the width of the field grid cell, m; v is the speed of the fertilizer spreader, m/s.

In the process of designing the VRF system, a good balance between mechanical movement reliability and response speed of variable rate adjustment should be taken into account. Therefore we set $t/2$ as a target limited response time for adjustment of the active feed-roll length from 0 to L_{max} (the maximum length of the fluted roller). Thus, the feed speed of adjustment lever v_1 (m/s) and the rotational speed of the cross lead screw nut v_2 (r/min) should satisfy the following relationships:

$$v_1 > \frac{L_{max}}{t/2} = \frac{L_{max}}{w/2v};\ v_2 > \frac{v_1}{d} > \frac{2L_{max} \cdot v}{w \cdot d} \tag{8}$$

where, d denotes the screw pitch of the feed adjusting lever. In general, the drill travels with a speed v = 1.67 m/s (6 km/h) in normal working conditions. The width of the field grid cell is w =19 m. The L_{max} and d are the inherent characteristics of the drill which can be measured by a vernier caliper. The measurement results are L_{max}=70 mm, d=1.75 mm/r. According to Equation (8), it is illustrated that:

$$v_2 > 422 \text{ r/min} \tag{9}$$

The operating torque of the cross lead screw nut was measured using a torque measuring wrench. When the fertilizer hopper is full, the maximum value of torque is 1.8 N·m across five repeated measurements. Based on the above evaluation, a dc servo motor (36SYK71, Saegmotor, China) with a planetary reducer was chosen as the VRF actuator. The reduction ratio of the planetary reducer is 16. A photo-electric coder is used as angle position sensor to get closed-loop control. The rated torque output is 2.7 N·m greater than 1.8 N·m, and the rated speed output is 443 r/min greater than 422 r/min as mentioned in Equation (9). The results showed that the servo-driven actuator met the design requirements. The installation structure is shown in Figure 2b.

2.2.2 The control strategy of VRF actuator

The position control mode of the servomechanism is used to adjust the active feed-roll length. This control mode is based on three-loop control strategy (Figure 3). The position loop is on the outermost layer. The final control precision is directly related to the result of the position loop control. The primary target of the position loop is to track the changes of commands quickly and accurately. The output of the position loop becomes the input for the velocity loop. The role of the velocity loop is to maintain smooth operation by controlling the speed of the motor. The output of the velocity loop becomes the input for the current loop. The current loop is the innermost layer of the servomechanism and it drives the motor. Proportional-integral-derivative (PID) control offers the simplest and yet most efficient solution to many real-world control problems[12]. Proportional item (P) is used for adjusting the response speed and controlling the error of the system. Integral item (I) speeds up the control process so that it approaches the set value and eliminates residual error that occurs with a pure proportional controller. Derivative item (D) can improve the dynamic characteristics of the control system, restrain and predict deviation. In this paper, PI control was used in current loop and velocity loop to achieve a quick response. PD control was used in position loop control due to the predictive nature of the derivative unit to avoid overshoot.

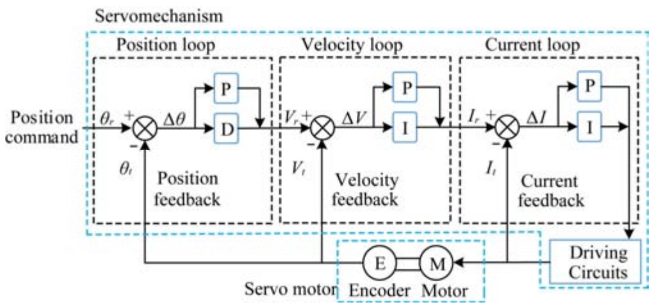


Figure 3 The control strategy of the servomechanism

2.3 Design of embedded VRF support decision subsystem

With the advantages of portability, integrated multifunctional and low-cost, the embedded controller is often used in industrial design. An embedded controller is composed of an embedded hardware and an operation system (system on chip). The embedded hardware Tiny 210 (Friendly ARM, China) with 512 MB RAM and 1 GHz processor was chosen as the hardware platform of the VRF support decision subsystem. As an excellent mobile OS, Android has powerful functionality, and a well-supported Global Position System (GPS) which is very important for the VRF system. The open design and portability of software made Android OS the ideal choice as the software platform for VRF embedded controller. Custom Android software was developed to complete the VRF support decision subsystem. For the custom software, the core function of spatial information queries and spatial location searches relies on the SpatiaLite database, which is an open source library intended to extend the SQLite core to support fully fledged Spatial SQL capabilities[13]. The prescription map which consists of a series of vector field grid cells and boundaries is saved in the form of a database by SpatiaLite. In the database, a record represents a vector field grid cell containing geographical information and fertilizer application rate data. The real-time map display is based on ArcGIS Runtime SDK for Android. The embedded hardware connects with a GPS receiver through the serial port (RS232) for receiving the latest location information of the fertilizer spreader. So by using the latitude and longitude information, the fertilizer application rate can be easily queried from the SpatiaLite database. The queried fertilizer application rate data, as a real-time control command, is sent to servomechanism through another serial port (RS232) to accomplish precise fertilizer use. The flowchart of VRF embedded controller development is shown in Figure 4.

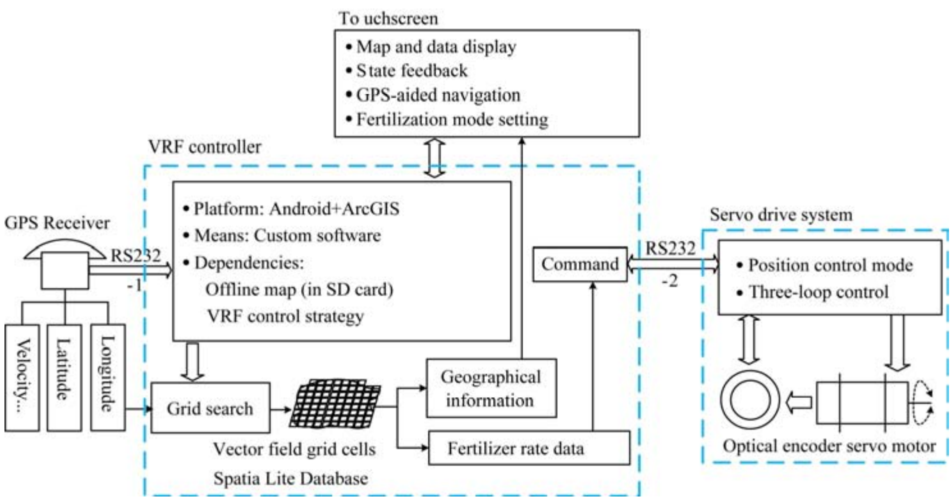


Figure 4 The flowchart of VRF embedded controller development

Since it is a closed loop control, the control result and status information are returned to the controller. A touchscreen is used as the software interface display for human-machine interaction. Users can see the real-time location of the fertilizer spreader and all the fertilization status information on the screen. The main interface of the custom software is shown in Figure 5.

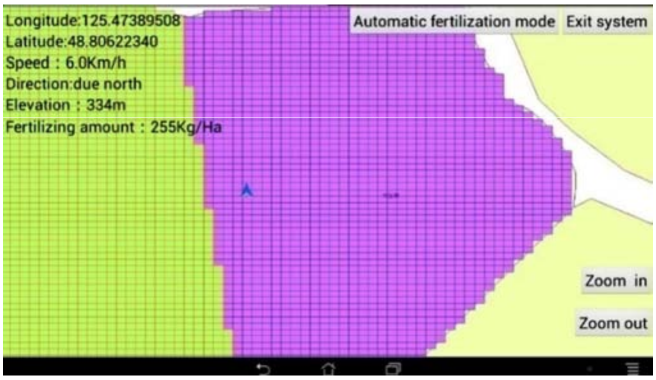


Figure 5 The main interface of the custom software

3 Results and discussion

3.1 Fertilization uniformity evaluation and model parameter fitting

The VRF process is consisted of the most uniform fertilization process for each specified field. The performance of uniform fertilization is an important feature for the VRF system. An indoor experiment based on uniform fertilization was carried out to test the fertilization uniformity of the VRF system. The spreader ground wheel was set at a simulated speed of 1.67 m/s and the row spacing L_2 was 0.7 m which was often adopted in corn planting. The experiment strategy was to measure the fertilizer application rate of the seven synchronous fluted rollers in different active feed-roll lengths. The maximum length of each fluted roller was 0.07 m. So when the active feed-roll length was set to 0.025, 0.03, 0.04, 0.05 and 0.06 m, the fertilizer application rates P (kg/min), discharged by seven synchronous fluted rollers in 1 min intervals, were measured respectively. The five groups data obtained from this experiment were analyzed in the Figure 6.

In Figure 6, there were seven red circles corresponding to the discharge rate of seven fluted rollers for each active feed-roll length. The box plots graphically showed the dispersion degree of the discharge rate of the seven fluted rollers. The coefficient of variation (CV) was typically used as an assessment verification indicator of fertilization uniformity[14-16]. The smaller CV value reflects better uniformity application performance. The CV values in five different active feed-roll lengths were shown in Table 1. The average CV value is 8.4%. Fulton et al.[15] set 20% of CV as an acceptable level of uniformity. So the results in this paper show good uniformity fertilization performance.

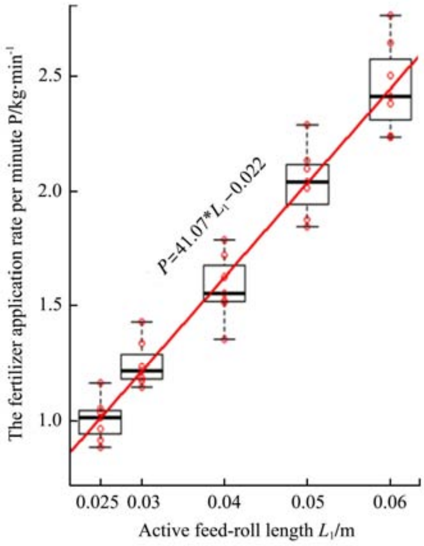


Figure 6 The performance analysis of uniform fertilization

Table 1 The CV values in different active feed-roll lengths L_1

L_1/m	0.025	0.03	0.04	0.05	0.06
CV/%	9.3	8.2	9.1	7.5	8.1

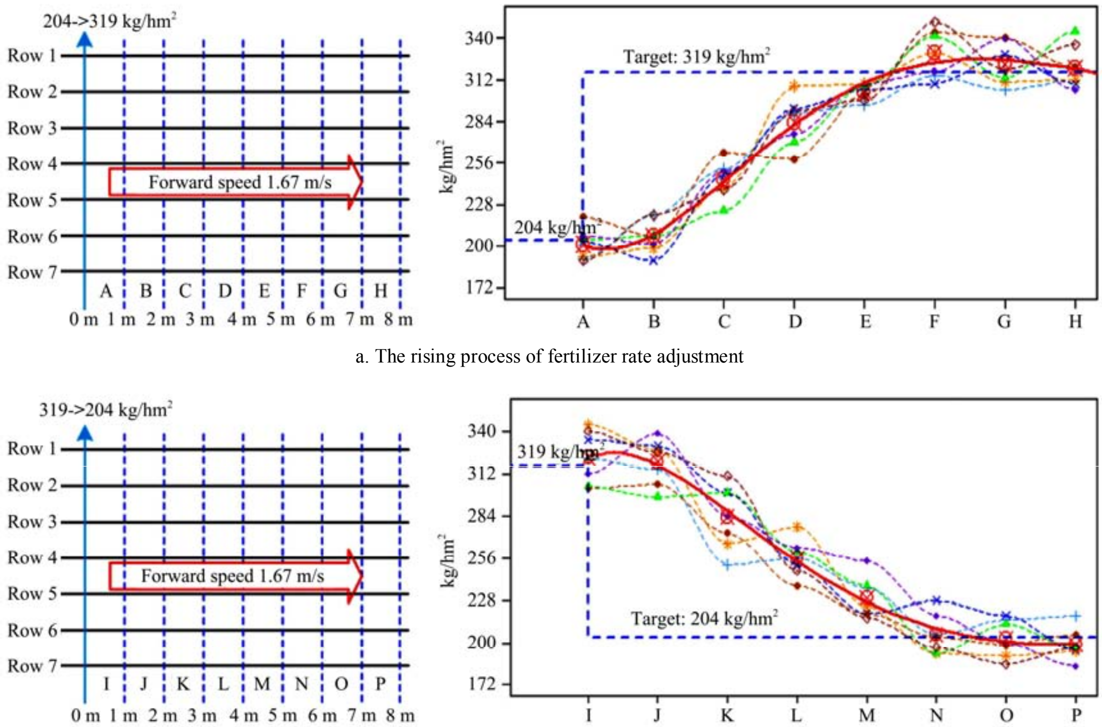
According to the linear-relationship between ΔM and L_1 in Equation (6), a linear equation is fitted based on the five groups data. The red line in Figure 6 represents the linear-relationship between the fertilizer application rate per minute P (kg/min) and active feed-roll length L_1 (m). The relationship between ΔM (kg/hm^2), P (kg/min) and L_1 (m) is as follows:

$$\Delta M(\text{kg/ hm}^2)=\frac{P(\text{kg/ min})}{S(\text{m}^2/\text{ min})}\cdot\frac{10^4\text{ m}^2}{1\text{hm}^2}=\frac{10^4\cdot P}{60v\cdot L_2}=142.85P=5867.7L_1-3.14 \quad (10)$$

Equation (10) is a numerical relationship between target fertilizer application rate and the active feed-roll length. The variable rate adjustment is based on this equation. The intercept term is the deviation from the fitting result.

3.2 Response time of variable rate adjustment

The response time of variable rate adjustment determined the performance of tracking the changes of the fertilizer application rate. A VRF experiment was conducted to analyze the system against its response time of on-the-go fertilizer adjustment. The fertilizer spreader passed over a flat cement area at 1.67 m/s with the application rate changing from 204 kg/hm^2 (L_1: 35 mm) to 319 kg/hm^2 (L_1: 55 mm) and 319 kg/hm^2 to 204 kg/hm^2. For each row, the discharged fertilizer at each meter interval was collected and weighted. The obtained data were analyzed in Figure 7.



b. The descent process of fertilizer rate adjustment

Figure 7 The performance analysis of VRF

The seven dash lines in Figures 7a and 7b present the variations between the fertilizer rate discharged by each fluted roller and the distance traveled, respectively. The red solid line which is generated by fitting the mean discharge rate from seven fluted rollers demonstrates the VRF performance of the fertilizer spreader. The rising (A-G) of fertilizer rate adjustment is almost symmetric with the descent of adjustment (I-O). Further analyzing the red solid line, the distance using variable rate adjustment is about 7 m. The response time of VRF system is about 4.2 s based on the forward speed 1.67 m/s. Compared to [17, 18], the response time doesn't have a noticeable improvement due to a compromise between the stability of the adjustment and response time. The adjustment range is 115 kg/hm^2 in this experiment. However, in practical application the actual adjustment range is a lot less than 115 kg/hm^2 from one grid field to an adjacent gird field which means the response time is shorter than 4.2 s. So the response performance of our VRF system is good enough for practical application.

4 Conclusions

Variable rate fertilization is of critical importance in the research of precision agriculture. A novel VRF system based on adjusting the active feed-roll length was successfully implemented in this paper. The control method based on adjusting the active feed-roll length achieved high precision control and quick response time because of a single control variable and a simple structure. A servo control mechanism was designed as the VRF actuator for the active feed-roll length adjustment. A low-cost and stable embedded VRF support decision subsystem was developed to co-operate with the actuator. The experimental results indicate that application uniformity is satisfied because the average CV value is 8.4% in five different active feed-roll lengths. The dynamic response times for the adjustment of fertilizer application rate from 204 kg/hm^2 to 319 kg/hm^2 and 319 kg/hm^2 to 204 kg/hm^2 are about 4.2 s. The VRF system exhibits good dynamic adjustment performance and stability.

Acknowledgements

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