Remnant fertilizer monitoring system for maize fertilizer applicators

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Abstract: A remnant fertilizer monitoring system utilizing three-dimensional (3D) reconstruction was proposed to detect the amount of remaining fertilizer in the applicator's tank. Bench tests were carried out to compare the performance of four algorithms to estimate the remnant fertilizer amount: fertilizer remnant monitoring biharmonic spline algorithm (V4), natural nearest-neighbor algorithm (Natural), linear algorithm (Linear), cubic algorithm (Cubic). The average relative error for remnant fertilizer monitoring is 7.33% for the Linear algorithm, 7.30% for the Natural algorithm, 5.18% for the Cubic algorithm, and 4.30% for the V4 algorithm. Field tests are conducted at three fertilization rates to compare the performances of the V4 and Cubic algorithms. The average relative error for discharged fertilizer monitoring is 8.64% for the Cubic algorithm, which is 1.91% lower than that of the V4 algorithm. The results show that the Cubic algorithm has the best performance for remnant fertilizer monitoring. The average relative error of remnant fertilizer monitoring is 2.42% for the Cubic algorithm, which is 0.43% lower than that of the V4 algorithm. The response time of the remnant fertilizer monitoring system is 0.26 s. The results demonstrate that the proposed remnant fertilizer monitoring system is highly accurate and suitable for real-time applications.

Keywords: maize fertilizer applicator, remnant fertilizer monitoring, 3D reconstruction, solid level detection
DOI: 10.25165/j.ijabe.20231605.7452

Citation: Zhang Y H, Zhang K L, Yu Y, Zhang D X, Yang L, Cui T, et al. Remnant fertilizer monitoring system for maize fertilizer applicators. Int J Agric & Biol Eng, 2023; 16(5): 173–180.

1 Introduction

Variable-rate Fertilization (VRF) is a precision agriculture method that reduces fertilizer impact on the environment[1-3]. A remnant fertilizer monitoring system provides crucial feedback to avoid insufficient discharge of fertilizer due to a lack of fertilizer in the storage tank and ensures the accuracy of variable-rate fertilizer applications[4-7].

Scholars have proposed different solutions for detecting the levels of materials. Resistive force sensors, capacitive sensors, and radar have been used to detect the liquid level in a storage tank. Recalibration of the sensor is required for different liquids[8-10]. Diaphragm transducers and Hall sensors have been used for hydrostatic level measurements of liquids[11]. The combination of three capacitive sensors has shown excellent performance[12]. Signal sensors are less costly integrated sensors, but the accuracy of level detection is worse[11-13]. The level detection of solids is more complex and differs from that of liquids[14]. The acoustic tube method was used to detect the level of hot powder and finely-grained solid materials[14,15]. The DC component of a microwave Doppler module was used to detect the level of liquid and solid materials in a nonmetallic tank[16]. The *K*-nearest neighbor (KNN) classifier and a gray-level aura matrix approach were used to establish an automated solid waste bin level detection system. However, this method could only detect whether the waste bin was full or not[17]. A capacitive sensor was designed for the online detection of the fertilizer level in the fertilizer storage tank[18,19]. The accuracy of the capacitive sensor was affected by temperature and humidity, and the accuracy of remnant fertilizer monitoring was affected by the stacking angle of the fertilizer[18,19]. A radar point cloud was used to detect remnant fertilizer, although it was time-consuming to add a mobile device to collect the point cloud data[20].

In summary, material-level detection sensors include capacitance sensors, pressure sensors, acoustic tube sensors, infrared sensors, and machine vision[11,14,16,17,21]. However, these methods are not suitable for remnant fertilizer monitoring due to the stacking angle of the fertilizer[19]. Some detection methods are affected by vibration and fertilizer type, making it challenging to obtain accurate estimates of the material level[16, 22]. Pressure sensors are not affected by humidity but are susceptible to vibration. Radar data have a long acquisition time and low detection frequency[20]. Thus, it is worthwhile to investigate methods to estimate the amount of remnant fertilizer in a storage tank in real time.

A remnant fertilizer monitoring system is proposed to ensure that the operator is aware of the remaining fertilizer amount in the tank. A fertilizer tank monitoring algorithm and three-dimensional (3D) reconstruction are used to detect volume changes of the fertilizer in the storage tank. The monitoring system is not affected by temperature, humidity, and the stacking angle of the fertilizer and has a short response time.

2 Materials and methods

Since the fertilization rate of the variable fertilizer applicator is changeable, it is impossible to judge the fertilizer tank allowance by

Received date: 2022-02-25 **Accepted date:** 2023-06-25
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experience. A fertilizer remnant monitoring system can avoid missing fertilizer applications because of a lack of fertilizer remaining information in the fertilizer tank. Next, the VRF system and fertilizer remaining monitoring system built in this study will be introduced respectively.

2.1 Variable-rate fertilizer system design and operating principles

As shown in Figure 1, the remnant fertilizer monitoring system is based on a 2BMYFS-4/4-4 maize no-tillage drill/fertilizer machine (Dahua Baolai, China), containing four fertilizer applicators and two fertilizer tanks. The fertilizer tank monitoring system is installed in the fertilizer tank.

The remnant fertilizer monitoring system platform includes a 2BMYFS-4/4-4 maize no-tillage drill/fertilizer machine (DahuaBaolai, China), MOTEC servo motor and driver (Germany), stepper motor push rod (China), Arduino controller (Italy), 12 V DC power supply (China), GPS (China), USB-CAN analyzer (China), MCP2515_CAN module (China), and a PC Machine (China).

The VRF system adjusts the rate of fertilizer application by controlling the length of the active feed roller and the rotational

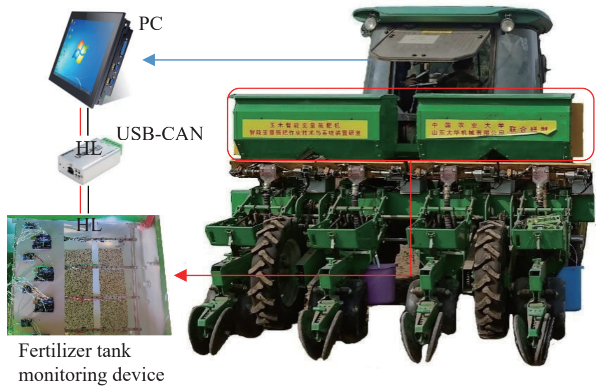


Figure 1 Framework of the remnant fertilizer monitoring system

speed of the shaft. The length of the active feed roller is the effective length of the outer groove wheel of the fertilizer discharge device. The VRF system is used as the test platform for the remnant fertilizer monitoring system. The connection diagram of the VRF system is shown in Figure 2. The working principle of the VRF system is as follows:

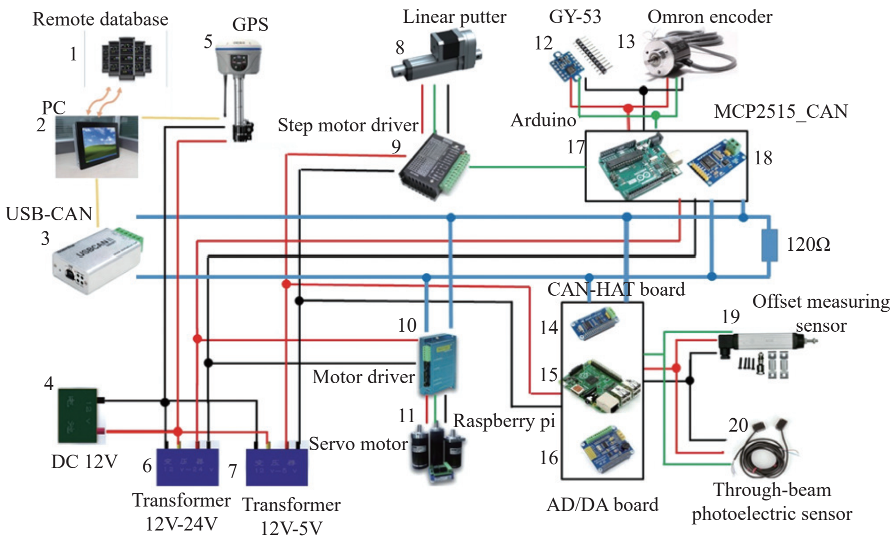


Figure 2 Connection diagram of the VRF system

1) The prescription, which contains the target fertilizer rate and the longitude and latitude information, is loaded into the PC;

2) The VRF system applies the required amount of fertilizer based on the GPS data and the prescription chart. The VRF system obtains information on the length of the active feed roll, the rotational speed of the drive shaft, and the status of the fertilizer pipe from the offset measuring sensor, Omron encoder, and the through-beam photoelectric sensor. The VRF system adjusts the working conditions based on the target fertilizer rate;

3) The VRF system sends the controller area network (CAN) commands to the MOTEC drivers and Arduinos through the PC, controlling the MOTEC servo motors and stepper motors to adjust the rotational speed of the drive shaft, the length of the active feed-roll, and the fertilizer rate.

2.2 Remnant fertilizer monitoring system and monitoring algorithms

The remnant fertilizer monitoring system is based on volume detection. This method is not affected by the external environment but only depends on the bulk density. We proposed a remnant fertilizer monitoring device based on 3D reconstruction to detect the remnant fertilizer in the tank (Figure 3). The monitoring system is installed at the top of the fertilizer tank.

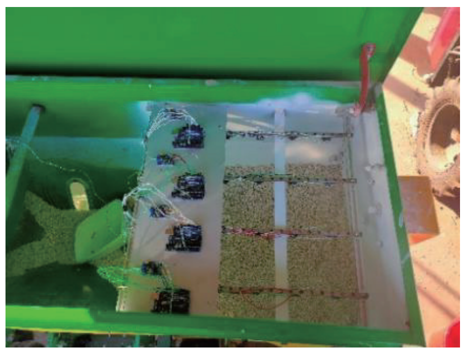


Figure 3 Remnant fertilizer monitoring device and its installation position

As shown in Figure 4, the remnant fertilizer monitoring system includes an Arduino controller, GY-53 infrared sensors, MCP2515_CAN modules, and a USB-CAN device. The information is transmitted from the Arduino controller to the PC through a CAN.

The working principle of the remnant fertilizer monitoring system is shown in Figure 5. The detailed steps are as follows:

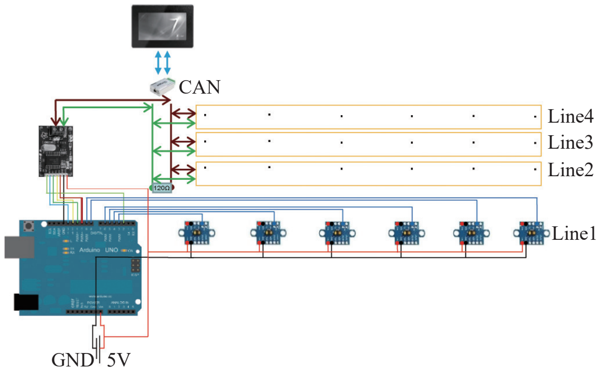


Figure 4 Connection diagram of the remnant fertilizer monitoring system

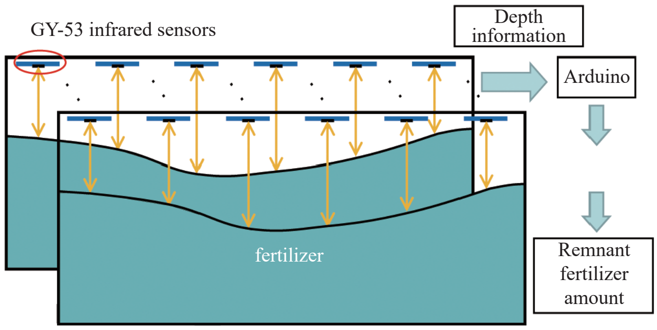


Figure 5 Working principle of the remnant fertilizer monitoring system

1) Multiple GY-53 infrared sensors are used to construct a lattice plane to determine the empty tank volume. The cross-sectional size of a single fertilizer box of the test prototype in this study is 50 cm×56 cm;

2) Multiple GY-53 infrared sensors are used to create a 4×6 lattice structure to detect the depth information of the fertilizer surface in the tank, and the length and width of the sensor grid is 14 cm×9 cm. The cyan area in Figure 5 shows the stacked fertilizer particles. The fertilizer is the white particles in Figure 3;

3) 3D reconstruction is used to reconstruct the surface. First divide the sensor plane into a 0.02 mm×0.02 mm grid. The points in the grid without depth data are then interpolated by interpolation based on the depth data. The volume between the sensor plane and the fertilizer surface is finally calculated from the interpolated depth data;

4) The difference between the volume of the calibrated empty tank and the volume between the sensor plane and the fertilizer surface is the volume of the remnant fertilizer in the tank;

5) The remaining amount of fertilizer in the tank and the output of the current shape of the fertilizer is calculated.

The volume change of the fertilizer in the tank was detected and the amount of discharged fertilizer was obtained according to the volume change and the bulk density as follows:

$$M_d = V_d \cdot \rho_a \tag{1}$$

The remaining amount of fertilizer in the fertilizer tank is calculated as follows:

$$M_l = M - M_a \tag{2}$$

Equation (3) is the detected amount of the remaining fertilizer in the tank.

$$M_{dl} = M - M_d \tag{3}$$

where, V_d is the detected change in the fertilizer volume in the fertilizer tank, L; ρ_a is the fertilizer's bulk density, g/L; M_a is the amount of discharged fertilizer in actual, kg; M_d is the detected amount of discharged fertilizer, kg; M_l is the remaining amount of fertilizer in the tank, kg; M_{dl} is the detected amount of the remaining fertilizer in the tank, kg; M is the total amount of fertilizer added to the tank, kg.

The horizontal plane of the fertilizer tank is rectangular. After the fertilizer has been discharged from the tank, the remaining fertilizer has a funnel shape, as shown in Figure 6. Therefore, two common sensor configurations are annular and matrix configurations. In the annular configuration, the sensors are placed in concentric rings. This configuration has the disadvantage that the depth information is close for all sensors in the same ring. Thus, the sensors should be arranged across the number of depth gradients to establish a reliable curve. The advantage of the matrix configuration is that it provides diverse depth information inside the fertilizer tank, and it is less costly to obtain a high-quality data set.

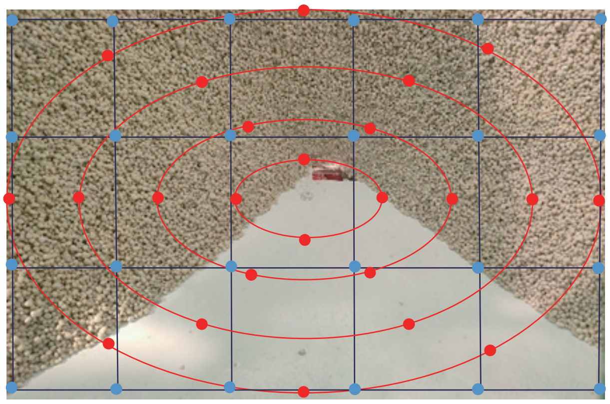


Figure 6 Depth information capture and parameter calculation (Red point and blue point are the GY-53 infrared sensors)

Because the depth information is discrete, four fertilizer remnant monitoring algorithms are designed to process depth data to get the fertilizer remnant information. The four fertilizer remnant monitoring algorithms are established based on biharmonic spline interpolation, natural nearest-neighbor interpolation, linear interpolation, and cubic interpolation. These fertilizer remnant monitoring algorithms are the V4 algorithm, Natural algorithm, Linear algorithm, and Cubic algorithm[23,24]. The main function of the remnant fertilizer monitoring algorithm is to perform threshold filtering on the depth signal to exclude outliers detected by the depth sensor. Subsequently, the algorithm interpolates the data and calculates the remnant amount of fertilizer in the tank. The workflow of the remnant fertilizer monitoring system is shown in Figure 7.

2.3 Fertilizer bulk density calibration test

The testing requirements of China's national standard for the control system of variable-rate fertilizer applicators (GB T35487-2017) were followed to test the proposed remnant fertilizer monitoring system[25]. Since the fertilizer in the tank is loosely packed, the China national standard GB/T 23771-2009 was used for the detection method of bulk density, using a 1 L container for repeated calibration tests[26]. The calibration equipment is shown in Figure 8. The bulk density of the fertilizer was 993 g/L.

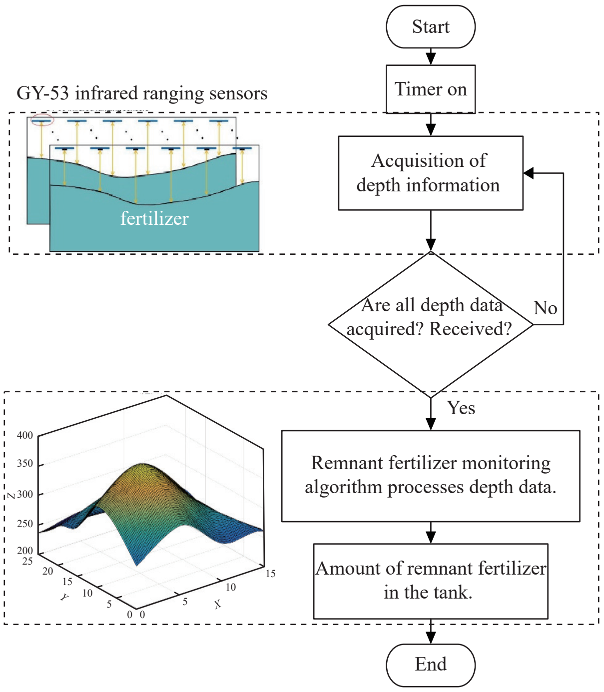


Figure 7 Depth information capture and parameter calculation

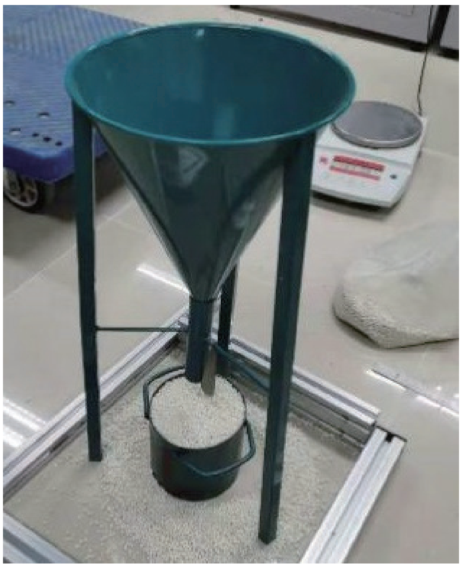


Figure 8 Calibration of the bulk density of the granular fertilizer

2.4 Evaluation experiment

2.4.1 Bench test

The bench test conditions are shown in Figure 9. In the preliminary comparison of the remnant fertilizer monitoring algorithm, 35 mm was used as the length of the active feed roll, and 10 r/min, 20 r/min, and 30 r/min were chosen as the rotational speed of the drive shaft. These working parameters are commonly used during fertilization. The fertilizer discharge time was 1 min. The total mass *M* of the fertilizer added to the fertilizer tank in each experiment was 27.6 kg. The remnant fertilizer monitoring system's response time was the time difference between the output of two adjacent detection results.

2.4.2 Field test

This experiment followed a previously described method for remnant fertilizer monitoring[4,5]. The test setup is shown in Figure 10. We placed a bucket under the fertilizer outlet to collect and weigh the fertilizer. The test was repeated three times to minimize errors. It was used that the same active feed-roll length (35 mm), rotational speeds (10, 20, and 30 r/min), same fertilizer discharge time (1 min), and mass of the fertilizer (27.6 kg) as in the bench test.

Figure 9 Bench test of the variable-rate fertilizer applicator and the remnant fertilizer monitoring system

Figure 10 Field test of remnant fertilizer monitoring

2.5 Evaluation indices

The GB T35487-2017 standard "National Standard for Variable Fertilizer Application Control System" was followed regarding the application precision and fertilizer amount[25].

The relative error of the remnant fertilizer monitoring method was calculated as follows:

$$\mathrm{BRE}=\left|\left(\frac{M_l-M_{dl}}{M_l}\right)\times 100\%\right| \tag{4}$$

where, BRE is the relative error of remnant fertilizer monitoring, %.

Since the relative error of the remnant fertilizer monitoring method is affected by the total amount of fertilizer (*M*) in the tank, the relative error of discharged fertilizer monitoring is used as an evaluation index. It is calculated as follows:

$$\mathrm{DRE}=\left|\frac{M_a-M_d}{M_a}\times 100\%\right| \tag{5}$$

where, DRE is the relative error of discharged fertilizer, %.

3 Results and discussion

3.1 Remnant fertilizer monitoring model

3.1.1 Model establishment

Experiments were carried out at three fertilizer discharge rates. The remnant fertilizer amount in the tank is affected by the fertilization rate and the time. Therefore, the relationship between the actual fertilizer amount and the estimated amount obtained from the 3D reconstruction method is linear at the three discharge rates, as shown in Figure 11.

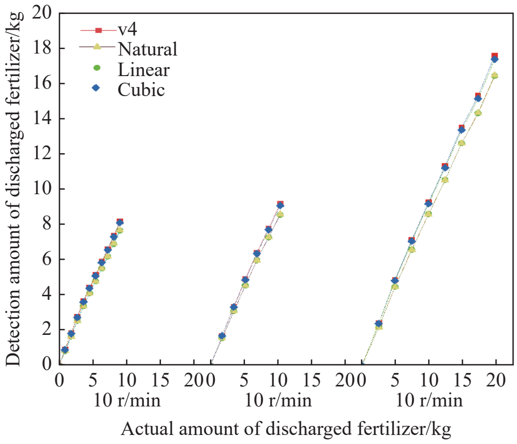


Figure 11 Actual and detection amounts of discharged fertilizer in the bench test

The determination coefficient R^2 of the regression equation was greater than 0.99, meeting the test requirements. The fitting equation at a single speed is not representative. Therefore, the detection results of the four interpolation methods were evaluated at three speeds. The calibrated regression models for the remnant fertilizer monitoring method using four algorithms are listed in Table 1.

Table 1 Calibrated regression model

Remnant fertilizer monitoring algorithm	Regression model
V4	$M_a = 1.1325M_d - 0.2969$, $R^2 = 0.9990$
Linear	$M_a = 1.2099M_d - 0.2499$, $R^2 = 0.9991$
Natural	$M_a = 1.2070M_d - 0.2353$, $R^2 = 0.9992$
Cubic	$M_a = 1.1470M_d - 0.2277$, $R^2 = 0.9989$

The operator can see the hollow left in the fertilizer tank after the fertilizer has been discharged. The peak in Figure 11 is equivalent to the hollow in the fertilizer tank, and T is the fertilization time, min. The length of the active feed roll is 35 mm, and the rotational speed of the drive shaft is 10 r/min. The height of the peak in Figure 12 increases with the fertilization time, which is consistent with the hollow left by the fertilizer discharged from the fertilizer tank.

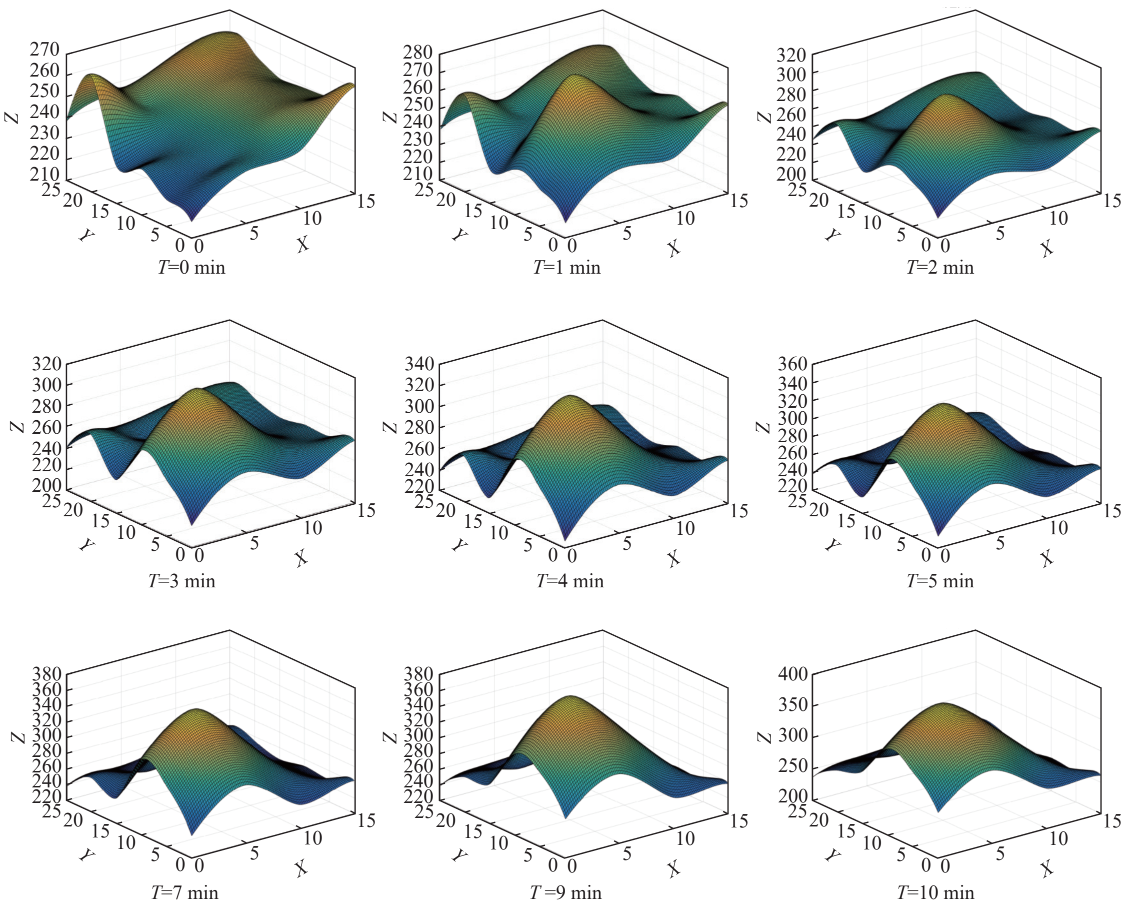


Figure 12 Graphs obtained from the remnant fertilizer monitoring system (Cubic) at different times

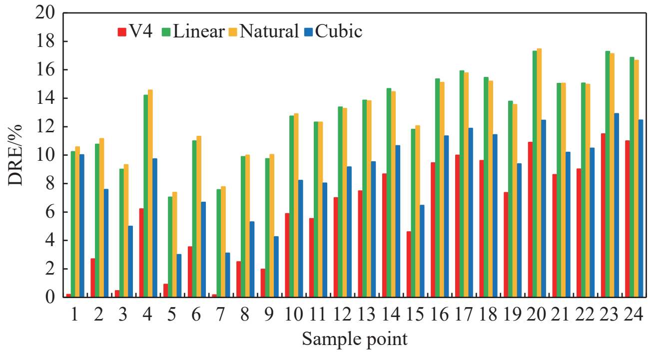
Table 2 lists that the average response time of the remnant fertilizer monitoring system is 0.26 s, meeting the real-time performance requirements.

Table 2 Response time of the remnant fertilizer monitoring system

Number	1	2	3	4	5	6	7	8	9
Response time/s	0.27	0.23	0.25	0.28	0.27	0.27	0.25	0.24	0.26

3.1.2 Monitoring accuracy

Figure 13 shows the relative error of discharged fertilizer monitoring in the bench test. The bench tests were carried out at three speeds to compare the four algorithms. The relative errors of the remnant fertilizer monitoring method are shown in Figure 14. The average relative error of discharged fertilizer monitoring is 12.93% for the Linear algorithm, 12.99% for the Natural algorithm, 8.72% for the Cubic algorithm, asnd 6.05% for the V4 algorithm.



Note: DRE is the relative error of discharged fertilizer, %.

Figure 13 Relative error of discharged fertilizer monitoring in the bench test

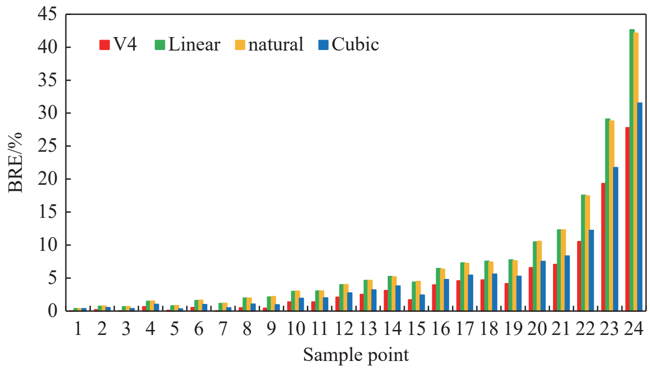


Figure 14 Relative error of remnant fertilizer monitoring in the bench test

The relative errors of remnant fertilizer monitoring are shown in Figure 14. The Linear and Natural algorithms show poor performance. The average relative error is 7.33% for the Linear algorithm, 7.3% for the Natural algorithm, 5.18% for the Cubic algorithm, and 4.3% for the V4 algorithm.

In summary, the V4 and Cubic algorithms show similar performance, meeting the detection requirements. These two methods provided higher performance for remnant fertilizer monitoring than the Natural and Linear algorithms. The relative errors of remnant fertilizer monitoring (BRE) and discharged fertilizer monitoring (DRE) increase with a decrease in the material level. Field tests were carried out to compare the performances of the V4 and Cubic algorithms to determine the optimum interpolation method.

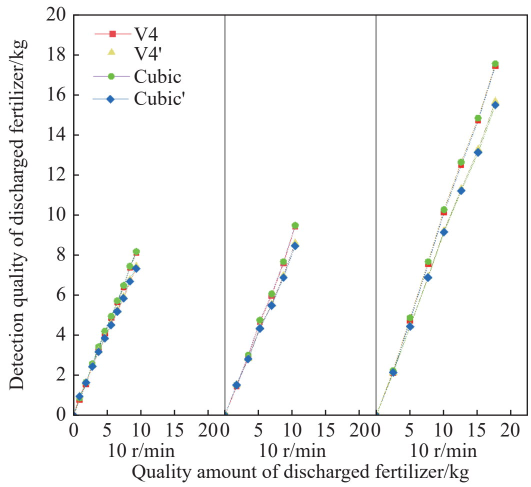
3.2 Field test results of the remnant fertilizer monitoring system

According to the conclusion of the bench experiment, the field experiment carried out further comparative experiments on the remnant fertilizer biharmonic spline algorithm (V4) and cubic algorithm (Cubic). The comparative analysis of the experimental results is as follows:

Regardless of whether the calibration model is used or not, the relationship between the actual and estimated amounts of fertilizer is linear (Figure 15), which is consistent with the calibration test results. In Figure 15, 10 r/min, 20 r/min, 30 r/min are arranged from small to large according to the actual fertilizer discharge, and Ma can be obtained as shown in Figure 16. Arrange the detected values V4, Cubic, V4', Cubic' and Ma correspondingly, and the V4, Cubic, V4', Cubic' curves can be obtained as shown in Figure 16.

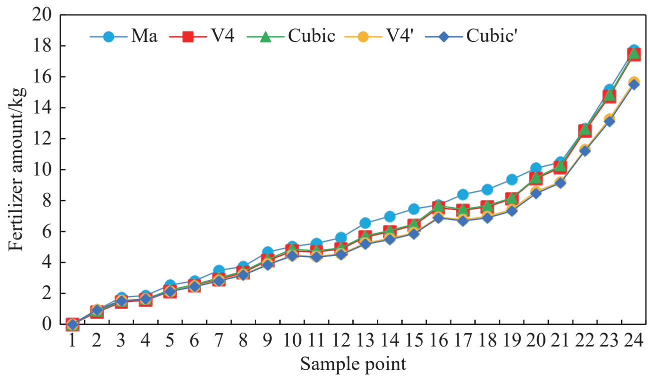
3.3 Comprehensive analysis of the field test

The relative errors of discharged fertilizer monitoring and remnant fertilizer monitoring indicate that using the calibration model provides better results than not using it (Figures 17 and 18).



Note: V4 and Cubic use the calibrated regression model, and V4' and Cubic' do not use the calibrated regression model.

Figure 15 Actual and detection amounts of discharged fertilizer in the field test



Note: V4 and Cubic use the calibrated regression model, and V4' and Cubic' do not use the calibrated regression model.

Figure 16 Actual and estimated amounts of discharged fertilizer in the field test

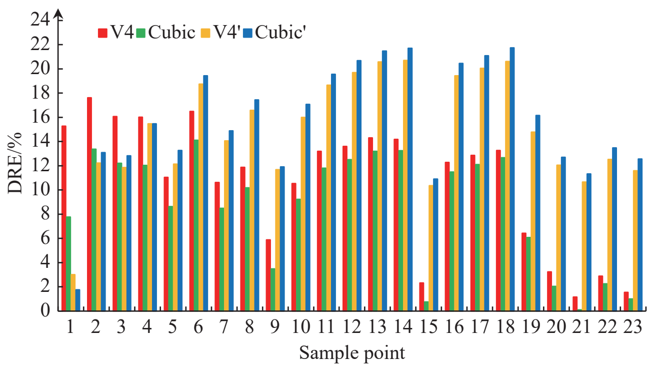


Figure 17 Relative error of discharged fertilizer monitoring in the field test

When using the calibration model for the fertilizer remnant biharmonic spline algorithm, the average relative error of the discharged fertilizer quality monitoring can decrease by 4.38%, and the average relative error of fertilizer remnant monitoring can be reduced by 2.9%. Similarly, using the calibration model for the fertilizer remnant cubic algorithm, the average relative error of the discharged fertilizer quality monitoring can decrease by 7.05%, and

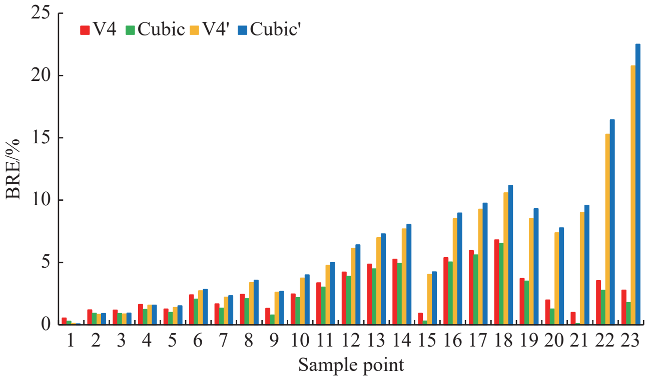


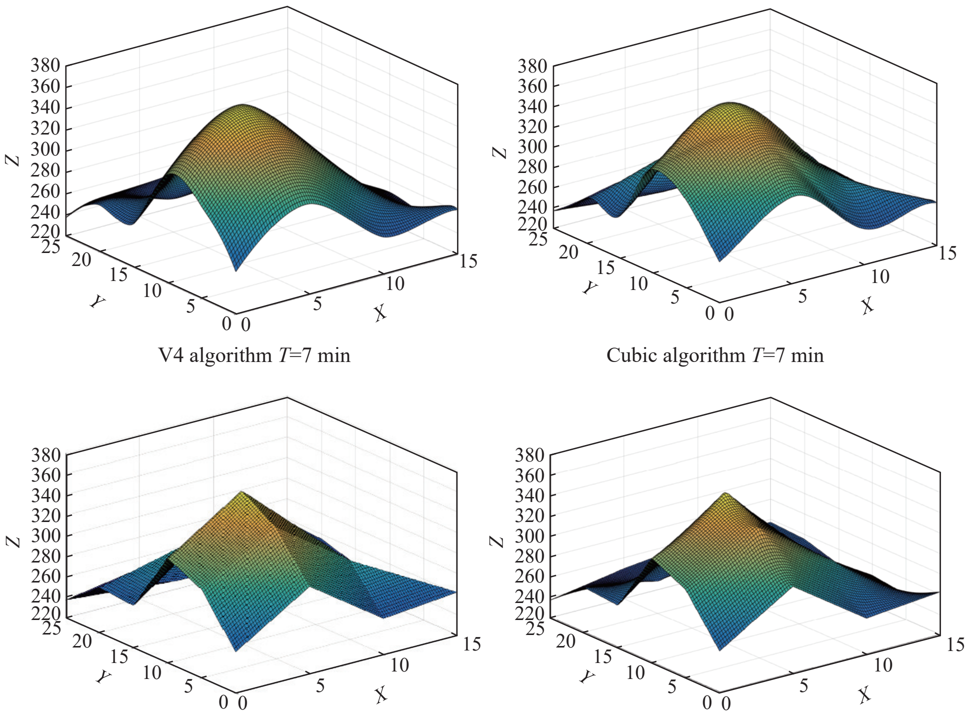
Figure 18 Relative error of remnant fertilizer monitoring in the field test

the average relative error of fertilizer remnant monitoring can be reduced by 3.96%.

The average relative errors of discharged fertilizer monitoring and remnant fertilizer monitoring in the 24 sets of data, the Cubic algorithm is higher than the V4 algorithm. The average relative error of discharged fertilizer monitoring is 10.55% for the V4 algorithm and 8.64% for the Cubic algorithm. Moreover, the relative errors of remnant fertilizer monitoring in the 24 sets are higher for the Cubic algorithm than for the V4 algorithm. The average relative error of remnant fertilizer monitoring is 2.85% for the V4 algorithm and 2.42% for the cubic algorithm.

The detection error of the system mainly comes from three aspects: sensor error, interpolation method, and depth information error caused by fertilizer flow. The interpolation method is a controllable factor of the relative fertilizer flow error, which allows us to improve the detection accuracy without increasing the cost of use. As can be seen from Figure 19, since friction is present between the particles, there is a stacking angle in the fertilizer. The surface shape of the fertilizer accumulation in the fertilizer tank is close to the inverted cone, and the stacked shape is not smooth. The reconstruction model of the remnant fertilizer monitoring algorithm is shown in Figure 20. Due to the different interpolation methods of the four algorithms, the reconstruction model obtained by the Cubic algorithm is more consistent with the surface shape of the fertilizer accumulation[23]. The V4 algorithm is smoother than the Cubic algorithm is smoother in the reconstructed model. However, this smoothing does not meet the surface shape of the fertilizer accumulation, when the bottom of the fertilizer box is exposed. so the surface shape of the fertilizer accumulation cannot be accurately reconstructed[24]. The surface shape of the fertilizer accumulation does not have edges and corners, but the shapes reconstructed by the Linear and the Natural algorithm have edges and corners. Therefore, the Linear and the Natural algorithm have a large difference in the surface shape of the rebuild and the surface shape of the fertilizer accumulation, so the monitoring errors are high.

Figure 19 Shape of the fertilizer accumulation T=7 min



V4 algorithm T=7 min

Cubic algorithm T=7 min

Linear algorithm T=7 min

Natural algorithm T=7 min

Figure 20 Reconstruction models of remnant fertilizer monitoring algorithm

The 3D reconstruction method has higher accuracy than the capacitance method for remnant fertilizer monitoring[27,28]. After more fertilizer is discharged, the bottom of the fertilizer box will be exposed, and the bottom is a flat surface. According to the comparison between V4 and Cubic in Figure 19, the reconstruction effect of Cubic is closer to the actual accumulation shape of fertilizer. The Cubic algorithm performed better than the V4 algorithm, and the calibration model improved the accuracy of remnant fertilizer monitoring.

4 Conclusions

A remnant fertilizer monitoring system that is unaffected by temperature, humidity, and the stacking angle of the fertilizer and has a short response time was developed. The remnant fertilizer monitoring algorithm used infrared ranging sensor data. Experiments were carried out for different fertilization rates. The following conclusions were obtained.

The Cubic algorithm provided better performance for remnant fertilizer monitoring than the V4 algorithm. The Cubic algorithm monitoring error was 1.91% lower than that of the V4 algorithm, and its average relative error of discharged fertilizer monitoring was 8.64%. For remnant fertilizer monitoring, the monitoring error of the Cubic algorithm was 0.43% lower than that of the V4 algorithm, and its average relative error was 2.42%. The response time of the remnant fertilizer monitoring system was 0.26 s.

Acknowledgements

This work was financially supported in part by the National Key R&D Program of China (Grant No. 2017YFD0700503) and the Soil-Machine-Plant key laboratory of the Ministry of Agriculture of China.

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