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Design and Experiments of a Convex Curved Surface Type Grain Yield Monitoring System

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Abstract: Precision agriculture relies heavily on measuring grain production per unit plot, and a grain flow monitoring system performs this using a combine harvester. In response to the high cost, complex structure, and low stability of the yield monitoring system for grain combine harvesters, the objective of this research was to design a convex curved grain mass flow sensor to improve the accuracy and practicality of grain yield monitoring. In addition, it involves the development of a grain yield monitoring system based on a cut-and-flow combine harvester prototype. This research examined the real output signal of the convex curved grain mass flow sensor. Errors caused by variations in terrain were reduced by establishing the zero point of the sensor's output. Measurement errors under different material characteristics, flow rates, and grain types were compared in indoor experiments, and the results were subsequently confirmed through field experiments. The results showed that a sensor with a cantilever beam-type elastic element and a well-constructed carrier plate may achieve a measurement error of less than 5%. After calibrating the sensor's zero and factors, it demonstrated a measurement error of less than 5% during the operation of the combine harvester. These experimental results align with the expected results and can provide valuable technical support for the widespread adoption of impulse grain flow detection technology. In future work, the impact of factors such as vehicle vibration will be addressed, and system accuracy will be improved through structural design or adaptive filtering processing to promote the commercialization of the system.



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1. Introduction

In the 21st century, precision agriculture stands at the forefront of agricultural science and technology. The objective is to maximize economic gains by optimizing various agricultural inputs, including water, pesticides, and fertilizers, to achieve maximum yields. Precision agriculture simultaneously seeks to reduce the use of chemicals, promoting ecosystem sustainability and environmental preservation [1,2]. The yield monitoring system is a key component of the precision agricultural technology system. Mapping the spatial distribution of crop yields is possible through the integration of yield-monitoring sensors into grain combine harvesters, which measure the real-time bulk flow of harvested crops. This process enables the estimation of total agricultural production and supports well-informed decisions regarding field management, as the derived data supports such calculations [3,4]. Therefore, the development of a grain harvester yield monitoring system for real-time measurement of grain flow information and yield data to enhance the level of automation and intelligence of China's harvesting machines is of great significance to the technological progress of the industry [5].

In terms of harvester size development, developed countries in Europe and America have significant advantages in the development and promotion of combine harvesters due

to their early start. In the mid-20th century, combine harvesters were widely promoted in countries such as the United States, the Soviet Union, Australia, Canada, etc. In order to improve the efficiency of combine harvester operations, the trend toward large-scale harvesters was developing [6]. On the one hand, the ultra-large combine harvester product represents the highest technological quantity, and on the other hand, it also declares the market position of agricultural machinery companies in the harvester industry. The engine power of the combine harvester continues to increase, the harvesting width expands, and the feeding amount increases, thereby improving the operational efficiency of the combine harvester and reducing production costs. The engine power of the LEXION 8900 combine harvester developed by German agricultural machinery manufacturer CLAAS and the Fendt IDEAL 10T combine harvester under the American Aiko Group both climbed to 580.7 kW, with a header width of 13.8 m and a grain tank capacity exceeding 15,000 L. The development of combine harvesters in our country began in the mid-20th century, with an early focus on imitating foreign models. With the continuous deepening of the reform, the opening up of the rural economic system, and the emergence of cross-regional agricultural machinery operation models, the combined harvester industry has developed rapidly [7]. The development of domestic grain harvesters in terms of size has made significant achievements, such as the World Dragon series 4LZ-3.5 tracked grain combine harvester, which is about 5.5 m long, 4.8 m wide, and 3 m high. The machine has a compact structure and moderate length, ensuring sufficient operating range and convenient transportation and transfer. The optimization of its size makes it more adaptable to the needs of different terrains and crop types, improving operational efficiency and effectiveness. Overall, China's grain harvesters have achieved significant growth in size, improving their operational efficiency and overall efficiency of agricultural production.

Developed nations such as Europe and the United States have made significant investments in human and material resources in the research and development of grain yield monitoring technology and systems. Efforts in this area have led to the development of several commercial grain yield monitoring systems and significant improvements in the requisite technology and equipment [8]. Shoji et al. [9] investigated a non-linear model for impact ring-type yield sensors with grain flow rate. They calibrated the model through field trials, which showed that the error in yield measurement was 3 to 5% when the grain flow rate was high and up to 10% when the grain flow rate was low. Reinke et al. [10] modeled grain flow in an uplifter by discrete element model simulation, which describes the relationship between the grain flow rate and the impact force on the impact plate. They explored the intrinsic factors affecting the accuracy of the model, with a maximum measurement error of 4.02% on a yield monitoring experiment bed. Still, the non-linearity of the model causes instability in the accuracy of the yield measurements. To develop a grain yield monitoring system suitable for China's national and agricultural conditions, the corresponding domestic researchers have also carried out much research. Chen et al. designed a single-plate impact grain flow sensor, completed the development of the hardware and software of the grain yield monitoring system, and developed a calibration experiment bed for grain flow sensors with an average error of 4.2% in yield measurement. Its measurement accuracy was greatly affected by vibration and other noise [11,12]. Zhou et al. improved an impact grain flow sensor by incorporating a double parallel beam structure. They developed an embedded signal acquisition and processing module. The results of the field yield experiment showed a maximum measurement error of less than 7.4% [13]. Zhao et al. proposed a grain thickness measurement method based on the near-infrared photoelectric effect. This method involves detecting the variations in light intensity as the grain passes through the laser transmitter and silicon photocells mounted on both sides of the grain elevator. This study examined the influence of infrared wavelength and laser power on measurement performance by fitting the Gaussian function equation to effectively improve the accuracy of photoelectric volumetric grain yield monitoring [14]. To reduce the error of machine vibration in yield monitoring, many scholars have proposed a monitoring method that involves installing photoelectric sensors on scraper-type grain elevators. For

example, Fu et al. developed a grain flow metering system based on the principle of photoelectric diffuse reflection. This system calculates the volume of grain by measuring the thickness of the grains on each scraper, achieving a more accurate measurement of the yield. However, due to the irregular stacking of the grains, a single photoelectric sensor falls short of providing complete characterization, and further improvements are needed to enhance the accuracy of yield monitoring [15].

From the above references, it can be inferred that the grain flow sensor, a critical component of the grain yield measurement system, can be bifurcated into two types: those premised on mass flow and those on volume flow. Due to their superior accuracy and stability, mass flow-based sensors have become standard for mainstream yield measurement systems in Europe and America. However, the technological prowess in this domain within China is considerably behind that of these foreign countries.

In recent years, China has made some progress in researching grain yield measurement systems, specifically those based on the principles of weighing mass flow and photoelectric volume flow. Nevertheless, these systems are still in the research stage due to their mechanical stability, installation and maintenance costs, and interface standards. Thus, there is an urgent need for continued research and development of practical grain yield measurement systems that can be seamlessly integrated and widely promoted within China. This research introduces a convex surface-type grain yield monitoring system in response to these challenges. The design process entailed establishing the yield monitoring principle, determining the overall structure, and developing software for this pressure-type grain yield monitoring system. This system enables essential operations, including parameter setup, data processing and collection, data presentation, and storage. An experimental rig was utilized to conduct a comparative study on grain mass flow rate.

Furthermore, a comparative analysis of grain mass flow sensors was carried out using an experimental stand and various parameters. Field evaluations were subsequently performed in various regions to validate the performance of the grain yield monitoring system. This research contributes to advancing grain yield monitoring technology, potentially helping China bridge the technological gap with other leading nations in this field.

2. Materials and Methods

2.1. Design of Key Components for Convex Surface Grain Yield Monitoring System

2.1.1. Design of Convex Surface Grain Mass Flow Sensor

The effectiveness of the mass flow sensor is crucial to the entire performance of the grain yield monitoring system, which is dependent on the precision of the mass flow sensor [16,17]. The grain yield monitoring system developed within this research study comprised components such as the sensor body support, signal conditioning module, and data processing module. In Figure 1, the monitoring system and the sensor body support are shown, mainly including the carrier plate, base, deflector plate, frame, vibration damper, connecting body, and cantilever beam-type elastic element. The base of the carrier plate is made of nylon and features a micro-convex curved shape, providing improved damping qualities and a smooth surface that simplifies processing. This specific shape enhances damping capacity, contributing to efficient vibration reduction. The shock absorber was arranged symmetrically at 4 points: one side was fixed on the frame, the other side was connected to the upper surface of the connector, the upper surface of the connector was perpendicular to the side surfaces, and there was a reinforcing bar welded between the two perpendicular surfaces. The cantilever beam-type elastic element was mounted on the side surfaces of the connector to minimize the effect of the vibration of the harvester on the accuracy of the measurement of the grain flow rate. A rectangular base with positioning holes separated the cantilever beam-type elastic element from the carrier plate.

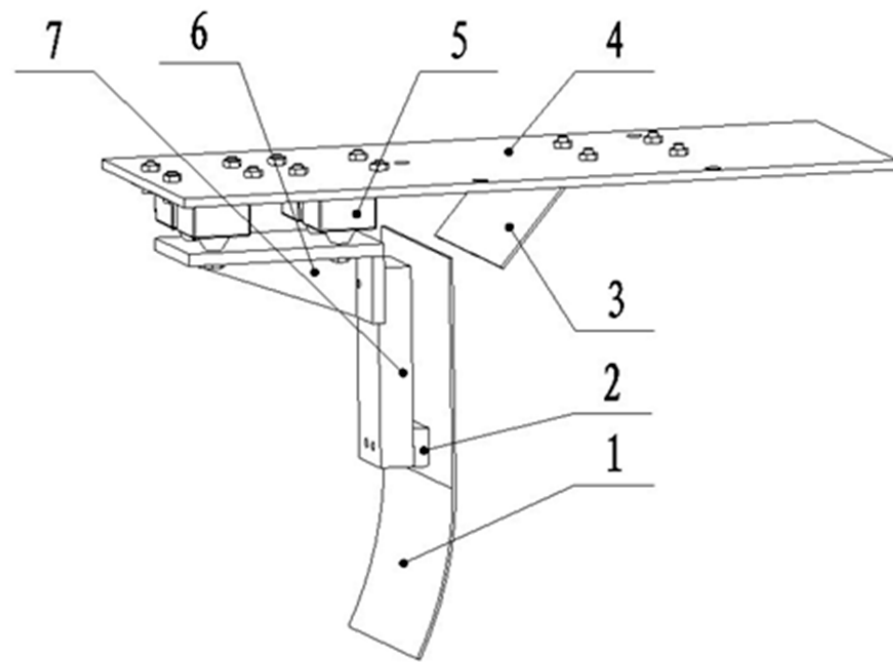


Figure 1. Convex Surface Grain Mass Flow Sensor. 1. Bearing plate, 2. Base, 3. Flow guide plate, 4. Frame, 5. Shock absorber, 6. Connecting body, 7. Elastic element.

2.1.2. Measurement Principle of Convex Surface Grain Mass Flow Sensor

The convex surface-type grain mass flow sensor was installed at the grain elevator outlet of the harvester. During operation, the grain in the elevator constantly impacts the bearing plate of the convex surface-type grain mass flow sensor through the action of the scraper. This impact, characterized by a specific speed and mass of grain that produced a certain amount of impulse, caused a lateral deviation in the cantilever beam elastic element of the convex surface-type grain mass flow sensor. According to the impulse theorem [18]:

$$F_{(t)} \cdot \Delta t = \Delta m_{(t)} \cdot \Delta v \quad (1)$$

$$F_{(t)} = \frac{\Delta m_{(t)} \cdot \Delta v}{\Delta t} = q_{(t)} \Delta v \quad (2)$$

In the formula, $F_{(t)}$ is the impact force of particles on the cantilever elastic element at time t ; Δt is particle impact time; $\Delta m_{(t)}$ is particle mass during the impact time at time t ; Δv is the change in velocity before and after particle impact; $q_{(t)}$ is particle mass flow rate at time t .

When Δt is very small, $q_{(t)}$ approximates the instantaneous mass flow. If the velocity difference is constant, then the impact force $F_{(t)}$ is approximately linearly related to the instantaneous mass flow rate of the particle. Mass flow data can be obtained by measuring the impact force.

In this paper, the impact force of particles on the carrier plate was obtained by a cantilever beam elastic element, the signal was conditioned by the transmitter, and the signal was filtered and extracted by an analog-to-digital converter and processor to realize the online real-time acquisition of mass flow data [19]. The transverse deformation of the cantilever beam-type elastic element is converted into a voltage signal by the resistance strain gauge bridge. The resistance strain gauge bridge further transformed this deformation into a voltage signal. The voltage exhibits an approximately linear relationship with the weight flow rate of the pellet within a certain range. Through calibration, the output voltage signal value can be translated into a particle mass flow value, allowing the measurement of the weight flow value at the inlet of the combined harvester grain tank per unit of time. The processor samples instantaneous particle mass flow rate data

through continuous timing and conducts data extraction and calibration operations to obtain the instantaneous particle mass flow rate data. These instantaneous flow values are accumulated to derive the cumulative mass flow value.

$$Q_i(t) = kN_i(t) + N_0 \quad (3)$$

$$W_i(t) = \sum_{i=1}^n Q_i(t) \quad (4)$$

In the formula, $Q_i(t)$ is the flow per second; k is the calibration coefficient; $N_i(t)$ is the average analog-to-digital conversion value per second; N_0 is the zero-value obtained by collecting the average flow rate value of the harvester under no-load conditions; $W_i(t)$ is the accumulated mass.

2.2. Design of a Monitoring System for Grain Yield Measuring Instrument

2.2.1. Hardware Equipment for the Monitoring System of the Grain Yield Measuring Instrument

The monitoring system of the grain yield measurement device employs the STM32F407 as its core processor. It is interconnected with the transmitter, memory, LCD screen, keys, and other peripherals via the interface circuit, as depicted in Figure 2. The STM32F407, produced by ST Company (Geneva, Switzerland), is a high-performance processor based on the Arm Cortex-M4 kernel. It integrates multifunctional interfaces, including ADC, LCD, Uart, SPI, and I2C. Specifically, the ADC interface is a multi-channel high-speed analog-to-digital converter with a 12-bit resolution and a maximum sampling rate of 2.4 MSPS. Considering that the signals from the cantilever elastic element and sensor are predominantly low-frequency, a hardware filter circuit is employed. This circuit connects the transmitter to the ADC interface, filtering out a portion of the interference signals. This facilitates software extraction of the actual signal, enabling precise capture of weight flow data. Following software processing, the data is stored in the W25Q128FV data memory in a specific format via the SPI interface. Subsequently, it is output to the LCD320240 LCD screen through the LCD interface for data, the selection of Shenzhen Jingcheng Display Technology Co., and waveform display. The system's operation and parameter modifications can be controlled by the operator using five keys. Other devices can access the system's status and measurement data through the RS485 interface. The 3.3VDC power supply required for the system work is provided by the Power Management unit, whose core element is the LM2575 switch voltage regulator integrated circuit, a 1A integrated voltage regulator circuit manufactured by National Semiconductor.

Given that the signal output from the convex curved surface-type grain mass flow sensor was in the range of 4–20 mV, which was relatively weak, amplification was required for accurate measurement. The GPR transmitter, manufactured by Shenzhen DMS Technology Development Co., Ltd. (Shenzhen, China), was employed for this purpose and supported by an arm-beam elastic element. External input was facilitated by five light-touch switches, forming a comprehensive set of man-machine interfaces along with an LCD screen. This configuration enabled convenient parameter adjustment and experimental data viewing. The data processing module could handle the requirements of acquiring, processing, and communicating weight and flow signals with these features. Figure 2 shows the hardware configuration of this system.

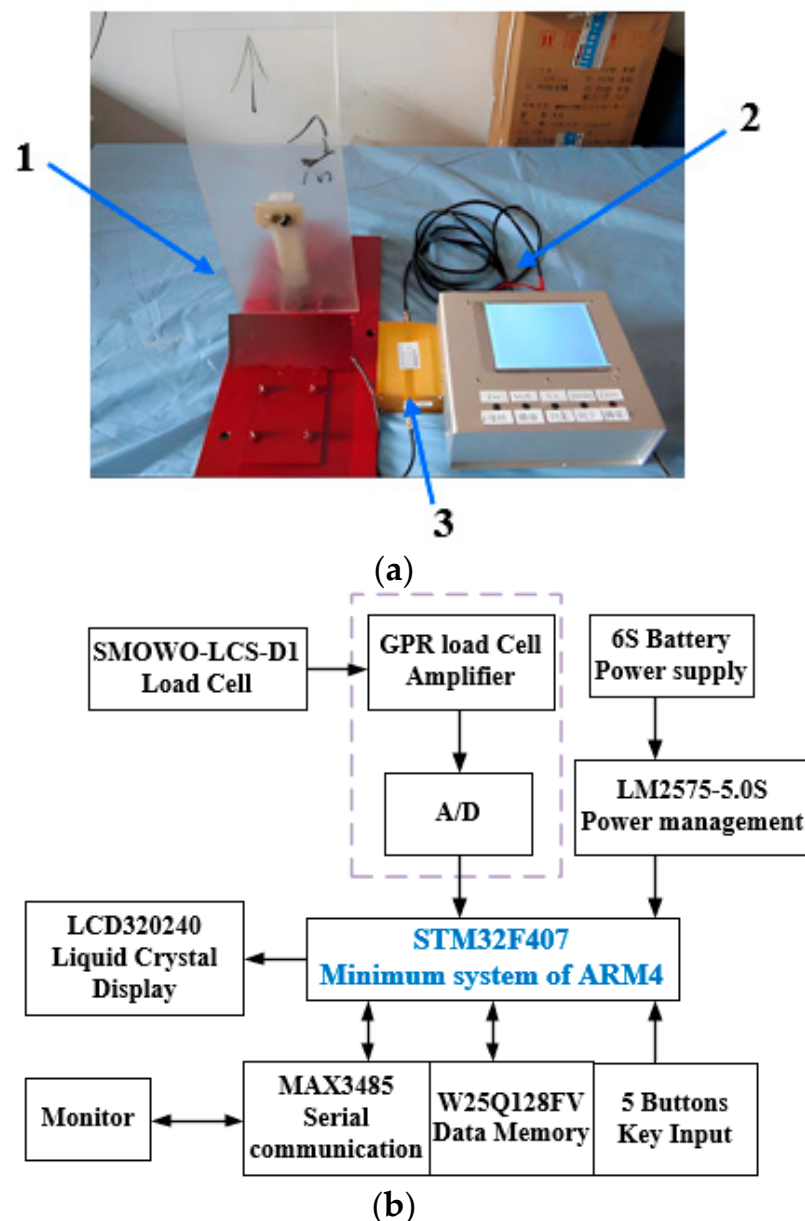


Figure 2. Hardware composition diagram. (a) Hardware physical combination diagram. 1. Grain mass flow sensor; 2. Grain yield tester; 3. CPR transmitter. (b) Hardware principal combination diagram.

2.2.2. Software Design of Grain Yield Monitoring System

After integrating the information from the various components, the grain yield monitoring system was run in an interface developed in the Keil MDK development environment [20,21]. The data processing program of the system was divided into three parts: the first part was the monitoring program, responsible for the system's power-on self-experiment, initialization, and similar functions. The second part was the application program, which calculated the weight flow rate, real-time display, and other related functions. The third part is the communication program that facilitates interactions with the multifunctional computer in the field. The whole software system adopts modular design ideas, and each module is linked by software structure, which is convenient for debugging, transplanting, and upgrading. According to the needs of the sensor application, the software system has the following functions: signal acquisition, data processing, update display, key processing, and data communication. The data processing function mainly implemented filtering the data, converting the scale, removing the zero position, and

obtaining and storing the flow rate data according to the given calculation method. The updating and displaying function implemented the real-time display of the instantaneous weight flow rate and the cumulative particle mass on the liquid crystal screen. The key processing function mainly responds to the information from different keys, executing corresponding operations and control functions. The lift impact process includes a gap feature intended to eliminate sensor drift, as shown in Figure 3 of the system program flow chart.

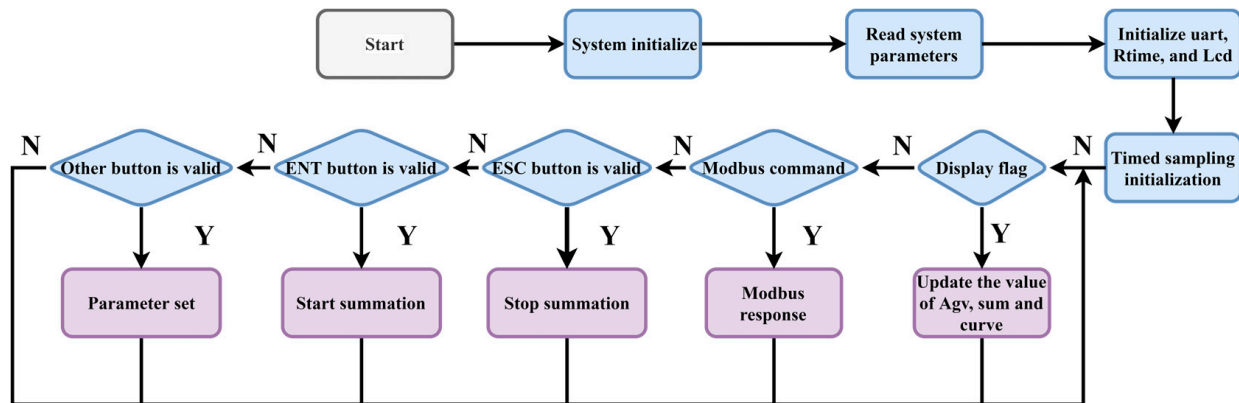


Figure 3. System program flowchart.

The overall working process of the system is as follows: 1. Power on self-test; 2. Start sampling timing; 3. When the sampling is completed, switch the DMA cache to continue collecting, filtering, non-linear correction, and dimensional conversion of the collected data, and set the update display flag. 4. If the display timer is reached and the updated display flag is valid, clear the flag and refresh the display of new data on the LCD screen. 5. If the RS485 interface receives unprocessed data, it responds according to the Modbus protocol and clears the flag; 6. Regularly execute key scanning, and if a key is pressed, perform functions such as starting accumulation, pausing accumulation, continuing accumulation, and parameter settings based on the key value. Loop through steps 3–6.

2.3. Bearing Plate Parameters and Design of Particle Mass Flow Simulation Loading Experiment Bench

The structural and installation parameters of convex surface grain mass flow sensors significantly impact measurement accuracy [22]. The curvature of the bearing plate can significantly affect the measurement results. Currently, there is no established theoretical calculation method to determine the optimal curvature of the convex curved surface grain mass flow sensor bearing plate. Therefore, it can only be determined through experimental methods. The structure and geometric parameters of the bearing plate are illustrated in Figure 4 and Table 1.

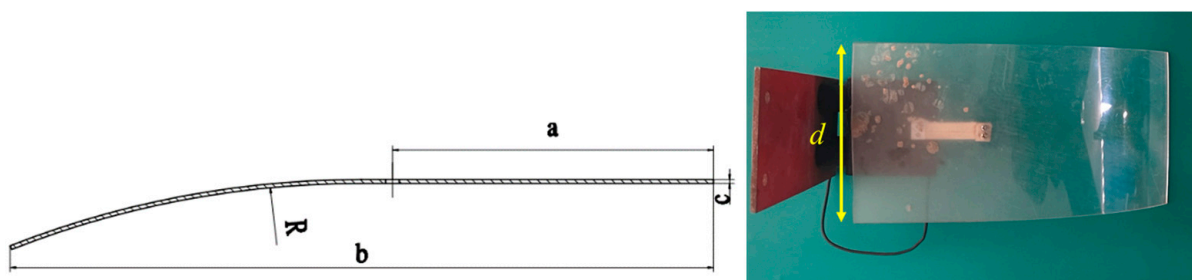


Figure 4. Structural diagram of the bearing plate.

Table 1. Geometric parameters of the bearing plate.

Group Number	Material	Unbent Length a\mm	Overall Length b\mm	Thickness c\mm	Curvature Radius R\mm	Width d\mm
①	Aluminum alloy	170	347	2	250	154
②	Aluminum alloy	170	347	3	250	154
③	Aluminum alloy	170	357	2	250	154
④	Aluminum alloy	170	357	3	250	154
⑤	Aluminum alloy	290	290	2	0	154
⑥	Organic glass	290	290	4	0	154
⑦	Organic glass	170	347	4	250	154
⑧	Organic glass	170	347	5	250	154
⑨	Organic glass	170	357	4	250	154
⑩	Organic glass	170	357	5	250	154

A particle mass flow simulation loading experiment bed was designed to carry out a series of experiments for calibrating the impact particle weight flow sensor, as shown in Figure 5. The experimental setup served as a simulation platform for particle mass flow, specifically designed for testing the combine harvester agitator cage and scraper lifter. Its main components comprised a Y112m motor, large and small belt pulleys, an agitator cage, a scraper lifter, brackets, inlet, and outlet boxes. Grain feeding was adjusted using a plug plate and three-phase asynchronous AC motor, Y112m, which boasted a 2.2 kW power capacity and operated at a rotational speed of 980 r/min. With a transmission ratio of 1:1.918, the center distance between the belt wheels was 698 mm, facilitating a stirring cage conveying speed of 511 r/min.

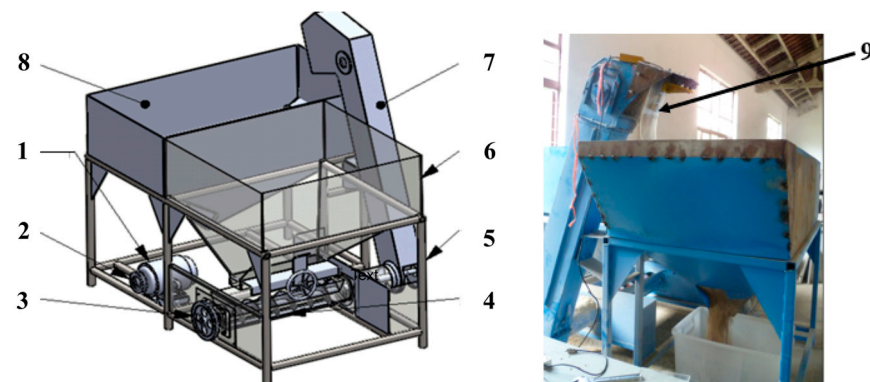


Figure 5. Particle mass flow simulation loading experiment bench. 1. Motor; 2. Small pulley; 3. Large pulley; 4. Stirring cage; 5. Platform; 6. Grain inlet tank; 7. Elevator; 8. Grain outlet device; 9. Flow sensor.

2.4. Field Experiment

Real-world harvesting conditions were used for field experiments to evaluate the calibrated system's measurement accuracy and the stability of the convex curved surface grain yield monitoring system. Convex curved surface grain yield monitoring system testing was conducted simultaneously on a cut longitudinal flow combine harvester prototype. Table 2 provides further information about this harvester, which was developed in cooperation with China Agricultural University, the Shenyang Institute of Automation of the Chinese Academy of Sciences, Jiangsu University, Foton Leiwo International Heavy Industry Co. Ltd., and China Machinery Southern Machinery Co. Field wheat harvesting was tested at Lianhu Farm in Danyang City, Jiangsu Province, and rice harvesting at Baoguanling Farm in Baohegang City, Heilongjiang Province. The field experiment status of the sensors is shown in Figure 6.

Table 2. Prototype parameters of a longitudinal flow combine harvester.

Parameters/Units	Value
Power configuration (kW)	128
Cutting width (m)	4.8
Rated feeding amount (kg/s)	6
External dimensions (mm × mm × mm)	7400 × 5785 × 3400
Engine speed (r/min)	2200
Whole machine weight (kg)	9020
Maximum walking speed (km/h)	20

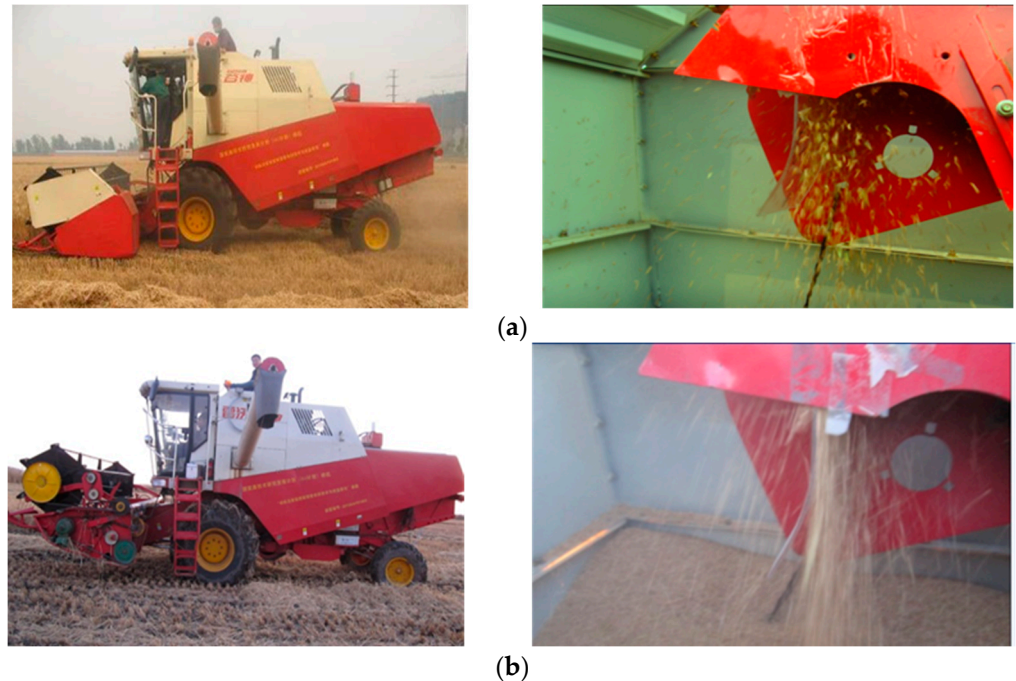


Figure 6. The working status of sensors in different field environment experiments. (a) The left side is a picture of the wheat experiment scenario, and the right side is a working picture of the system. (b) The left side is a picture of the rice experiment scenario and the right side is a working picture of the system.

3. Results and Discussion

3.1. Calibration Experiments of the Grain Yield Monitoring System

As the carrier plate, base, and cantilever beam elastic element all possess a specific mass, the gravity generated by this mass contributes to a measurable output on the sensor. Furthermore, fluctuations in the topography of the agricultural land may cause varying degrees of tilting in the elastic elements of the carrier plate, base, and cantilever beam. The modification of the gravitational force in the sensitive direction of the cantilever beam elastic element could lead to an unexpected dynamic shift in the zero point of the particle mass flow sensor output [23]. Therefore, it is necessary to take measures to determine the real-time output zero point of the convex curved surface-type particle mass flow sensor. This is essential for eliminating errors in the particle mass flow sensor caused by changes in ground conditions. The average value of the output voltage of the particle mass flow sensor under no load conditions was about 0.3 V.

The calibration equations changed when the parameters of the impact-type particle mass flow sensor's carrier plate and the range of the elastic element changed, so calibration was required before testing. During the calibration process, the totalization start button of the particle mass flow sensor was pressed. The experiment grains were poured into the grain inlet device of the particle flow experiment stand until they completely passed

through the carrier plate of the impact particle mass flow sensor. The totalization stop button was pressed, the cumulative mass output from the particle mass flow sensor was recorded, and an electronic scale was used to accurately measure the actual weight of wheat inside the grain outlet device of the particle flow experiment stand. The data records of the calibration experiment are presented in Table 3.

Table 3. Data of the calibration test.

Serial Number	Display Mass/kg	Actual Mass/kg	Relative Error/%	Calibration Coefficient	Mean Calibration Coefficient
1	14.99	19.89	−24.64	29,350	29,347
2	20.8	24.19	−14.02	31,923	
3	18.46	20.84	−11.42	31,197	
4	20.99	23.3	−11.01	24,918	

3.2. Analysis of Comparison Results of Bearing Plate Parameters

The experimental data related to geometric parameters of the convex surface type grain mass flow sensor bearing plate is presented in Table 4. The material, thickness, length, and curvature radius of the bearing plate significantly impacted the accuracy of grain flow measurement. When the grain flow rate was within the range of 0–2 kg/s and an elastic element with a range of 3 kg was selected, the smallest average relative error in grain flow measurement was achieved when using an organic glass bearing plate with a length (b) of 357 mm, a thickness (c) of 4 mm, and a curvature radius (R) of 250 mm, with a value of 2.27%. Conversely, selecting an aluminum alloy bearing plate with a length (b) of 357 mm, a thickness (c) of 3 mm, and a curvature radius (R) of 250 mm resulted in the highest average relative error of grain flow measurement, reaching 7.95%. The average relative error in minimum grain flow measurement was reduced by 5.68% compared to the average relative error in maximum grain flow measurement.

Table 4. Experiment data when the geometric parameters of the bearing plate change.

Serial Number	Group Number	Display Mass/kg	Actual Mass/kg	Relative Error/%	Relative Error Variance
1	①	24.29	23.72	3.25	3.59
2	①	22.68	22.09	3.12	
3	②	22.23	21.04	5.66	
4	②	21.75	20.54	5.89	
5	③	23.25	22.64	2.70	
6	③	22.39	21.84	2.52	
7	④	24.33	21.84	7.22	
8	④	23.68	22.69	8.67	
9	⑤	25.49	21.79	6.47	
10	⑤	25.24	23.94	6.09	
11	⑥	23.91	25.59	6.07	
12	⑥	23.22	22.54	6.80	
13	⑦	18.45	17.92	2.96	
14	⑦	28.07	27.13	3.47	
15	⑧	17.65	16.79	5.12	
16	⑧	18.23	17.29	5.44	
17	⑨	17.1	17.52	2.40	
18	⑨	18.53	18.14	2.14	
19	⑩	26.95	21.74	6.18	
20	⑩	25.20	23.92	5.36	

3.3. Analysis of Sensor Accuracy under Different Flow Rates and Particle Types

3.3.1. Analysis of Sensor Accuracy under Different Flow Rates

Simulations were conducted to assess the adaptability, reliability, and stability of the convex surface grain yield monitoring system. The measurements were evaluated under various flow rates by adjusting the feeding inlet position of the device on the experiment bench across gear settings from 1 to 5. The sensor, equipped with an organic glass bearing plate (length $b = 357$ mm, thickness $c = 3$ mm, curvature radius $R = 250$ mm) and a cantilever beam-type elastic element with a range of 0–2 kg, produced experimental data detailed in Table 5.

Table 5. Experimental data on changes in particle flow rate.

Serial Number	Gear Position	Display Mass/kg	Actual Mass/kg	Time/s	Average Flow/kg · s ⁻¹	Relative Error/%	Relative Error Variance
1	1	22.97	23.29	24.17	0.963	1.37	3.03
2	1	47.35	48.08	48.75	0.986	1.52	
3	2	28.64	28.26	18.38	1.538	1.34	
4	2	52.06	51.43	34.73	1.489	1.23	
5	3	28.96	29.49	14.54	2.028	1.80	
6	3	49.96	50.76	24.81	2.054	1.96	
7	4	27.5	26.89	11.3	2.380	2.27	
8	4	52.07	50.88	21.83	2.330	2.34	
9	5	25.03	23.75	8.41	2.824	5.39	
10	5	47.73	44.99	15.5	2.902	6.09	

The results highlighted a direct correlation between particle flow rate and measurement accuracy. Optimal accuracy was achieved in the 0–2 kg/s range. However, as the particle flow rate increased, the average relative error in particle flow rate measurement gradually escalated. Notably, when the particle flow rate exceeded 2.5 kg/s, the average relative error surpassed 5%.

3.3.2. The Influence of Particle Type on Sensor Accuracy

Comparative experiments were conducted on wheat and rice as experimental materials with different particle sizes using the same load-bearing plate and cantilever elastic element as employed in the above experiment to verify the accuracy of the sensor. The experiment was conducted on a particle mass flow simulation loading experiment bench with the same method and parameters for comparison. Detailed experiment results are presented in Tables 6 and 7.

Table 6. Experimental data of particle weight flow sensor using wheat as an experimental material.

Serial Number	Display Mass/kg	Actual Mass/kg	Time/s	Average Flow Rate/kg · s ⁻¹	Relative Error/%	Relative Error Variance
1	25.23	24.24	14.72	1.64	4.08	2.09
2	25.1	24.74	14.9	1.66	1.46	
3	25.03	24.29	17.91	1.24	3.04	
4	22.37	22.44	15.41	1.45	0.31	
5	23.7	22.79	19.09	1.20	3.99	
6	21.88	21.34	15.62	1.37	2.53	
7	22.04	21.94	15.03	1.46	0.46	
8	20.10	20.94	13.91	1.50	4.01	
9	21.10	20.84	15.37	1.36	1.25	
10	20.73	20.34	16.97	1.20	1.92	

Table 7. Experimental data of particle weight flow sensor using rice as experimental material.

Serial Number	Display Mass/kg	Actual Mass/kg	Time/s	Average Flow Rate/kg · s ^{−1}	Relative Error/%	Relative Error Variance
1	23.15	24.04	23.13	1.04	3.7	2.27
2	22.97	22.79	23.27	0.95	0.08	
3	21.6	22.24	21.22	1.05	2.9	
4	20.78	20.89	21.00	0.99	0.52	
5	20.21	20.64	20.04	1.03	2.08	
6	19.24	19.14	20.85	0.92	0.52	
7	23.58	25.26	22.73	1.11	3.73	
8	24.62	25.24	22.00	1.15	2.46	
9	24.04	24.94	19.84	1.32	3.61	
10	23.31	23.24	21.38	1.08	0.30	

From the above experimental data, the error of the sensor in measuring wheat and rice was approximately 4%, and there was no significant difference. Due to the size of the grain receiving basket, each experiment cannot exceed 55 kg. Analysis of the experimental data revealed that at an average grain flow rate of 0–2.5 kg/s, the maximum error was 2.339%. However, this error gradually increased when the average grain flow rate surpassed 2 kg/s. Notably, when the average grain flow rate exceeded 2.5 kg/s, the error surpassed 5%. Given that the average grain flow rate of the combine harvester was not more than 2.0 kg/s, the monitoring system operated reliably on the experiment bench, demonstrating stable performance and high accuracy.

3.4. Analysis of Field Experiment Results of the Grain Yield Monitoring System

Before the experiment, calibration was carried out to determine the calibration coefficient (k), zero position (N_0), and instantaneous flow rate (Q_0) displayed by the grain yield measuring instrument under no-load conditions. Throughout the experiment, the ground personnel directed operators of the grain yield measuring instrument and the grain receiving personnel to conduct simultaneous experiments. Due to objective limitations, the experiment was exclusively carried out using the manual grain-receiving method in the grain bin. Furthermore, the load was limited to a maximum of 50 kg in each trial due to the size of the grain-receiving basket. The experimental data is presented in Tables 8 and 9. The system was tested for performance on the day of the experiment and showed an accuracy of the production measurement error of less than 5%. To better demonstrate the performance of the system designed in this article, it was compared with the reference results mentioned in Table 10. It can be seen from these compared results of other references that the relative error of this article in different field harvesting scenarios is lower than that of the compared references, and the system stability is maintained when tested on the harvester.

Table 8. Field wheat harvest experiment data.

Serial Number	Display Mass/kg	Actual Mass/kg	Time/s	Average Flow Rate/kg · s ^{−1}	Relative Error/%	Relative Error Variance
1	27.29	28.35	27.4	1.035	3.74	2.35
2	33.64	34.69	24.88	1.394	3.03	
3	33.24	34.09	25.44	1.340	2.46	
4	41.66	43.54	35.5	1.266	4.32	
5	46.58	46.74	36.12	1.318	0.34	

Table 9. Field rice harvest experiment data.

Serial Number	Display Mass/kg	Actual Mass/kg	Time/s	Average Flow Rate/kg · s ^{−1}	Relative Error/%	Relative Error Variance
1	27.93	26.94	15.4	1.75	3.75	1.51
2	19.78	20.68	11.2	1.85	4.36	
3	32.36	31.09	23.4	1.33	3.91	
4	40.28	40.84	20.5	1.99	1.38	
5	36.21	37.09	36.8	1.03	2.44	

Table 10. Comparison results with existing references.

Reference	Sensor	Relative Error Range/%
Shoji et al. [9]	Impact ring-type yield sensor	The yield measurement error ranged from 3–5% at high grain flow rates to 10% at low flow rates.
Reinke et al. [10]	Mass flow yield sensor	The yield monitoring experiment bed showed a maximum measurement error of 4.02%, but the obtained data was unstable.
Chen et al. [11]	Single-plate impact grain flow sensor	The experimental platform recorded a 4.2% maximum error.
Chu et al. [12]	Single-plate impact grain flow sensor	It was vibration-sensitive and untested in real field conditions.
Zhou et al. [13]	Impact grain flow sensor	The results of the field yield experiment showed a maximum measurement error of less than 7.4%.
Proposed method (This research)	Convex Surface Grain Mass Flow Sensor	The measurement error while the combine harvester was used was less than 5%.

4. Conclusions

A grain yield monitoring system with a convex curved surface design was devised to meet the current operational requirements of intelligent harvesters in China. The main content of this research was divided into two key aspects: the development of grain yield measuring instruments and experimental research. The main research work is summarized as follows:

- (1) The overall functional analysis and hardware scheme design of the grain flow monitoring device of the combine harvester has been completed. The principles of key component design were analyzed, and the monitoring unit of the grain yield meter, including the controller, keypad, display, etc., was designed. In the main controller development platform, Keil5 is the main program and the main control unit of the underlying driver subroutine design. The main program of the system was compiled, with a primary emphasis on completing system initialization, key recognition, signal acquisition, flow calculation, display functions, and communication with the field computer. Finally, online yield measurement of grain combine harvesters was achieved based on the impulse theorem.
- (2) Functional debugging, indoor bench validation experiments, and onboard field harvesting experiments of the grain flow monitoring device for combine harvesters were completed. The simulated loading experiment on the experiment bench demonstrated that the measurement errors of the designed grain weight flow sensor are all less than 5% after calibration. With stable performance, easy installation, and operational suitability, the device meets the requirements for online measurement during combine harvester operations. The experiment compared the effects of five geometric parameters, including material, length, thickness, and curvature radius, on the accuracy of grain mass flow measurement for the load-bearing plate-type grain mass flow sensor. Comparison shows that the average relative error of grain mass flow measurement for the organic glass bearing plate with a length of $b = 357$ mm, a thickness of $c = 4$ mm, and a curvature radius of $R = 250$ mm is the smallest, with a value of 2.27%. The average relative error of grain mass flow measurement for aluminum alloy bearing

- plates with a length of $b = 357$ mm, a thickness of $c = 3$ mm, and a curvature radius of $R = 250$ mm is the highest, with a value of 7.95%. The average relative error of the minimum grain mass flow rate measurement is reduced by 5% compared to the average relative error of the maximum grain mass flow rate measurement 5.68%.
- (3) Post-calibration of the sensor's zero position and coefficients for different flow rates and grain types resulted in most errors being less than 5%. Indoor experiments compared the relative errors of the convex surface type yield monitoring system under different flow rates, and the data showed that at an actual average grain flow rate of 0–2.5 kg/s, the maximum error observed was 2.339%. When the actual average flow rate of the grain was more than 2 kg/s, the error increased gradually, and when the average grain flow rate exceeded 2.5 kg/s, the error exceeded 5%. The field experiments showed that the overall performance of the monitoring system was good. The system exhibited robust adaptability to various interference signals in the field, measuring yield online with an error of less than 5%.
 - (4) Although the sensor currently meets production testing needs, the system can be easily and effectively applied to rice and wheat harvesting scenarios. However, the measurement accuracy of the convex curved surface-type grain mass flow sensor is affected by vibration signals such as humidity, elevator speed, changes in vehicle forward speed, combined harvester body vibration, and ground impact. This leaves ample room for system upgrades. In future research, a filter could be designed by analyzing the vibration signals and using adaptive noise cancellation technology to achieve the filtering of vibration interference signals. Additionally, the stability and practicality of the system need to be repeatedly tested to further improve the stability and accuracy of grain flow sensors, allowing for commercialization and promotion in more crop yield monitoring scenarios.

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References

- Karunathilake, E.; Le, A.T.; Heo, S.; Chung, Y.S.; Mansoor, S. The path to smart farming: Innovations and opportunities in precision agriculture. *Agriculture* **2023**, *13*, 1593. [\[CrossRef\]](#)
- Gebbers, R.; Adamchuk, V.I. Precision agriculture and food security. *Science* **2010**, *327*, 828–831. [\[CrossRef\]](#) [\[PubMed\]](#)
- Finger, R.; Swinton, S.M.; El Benni, N.; Walter, A. Precision farming at the nexus of agricultural production and the environment. *Annu. Rev. Resour. Econ.* **2019**, *11*, 313–335. [\[CrossRef\]](#)
- Sharma, S.; Rout, K.; Khanda, C.; Tripathi, R.; Shahid, M.; Nayak, A.; Satpathy, S.; Banik, N.C.; Iftikar, W.; Parida, N. Field-specific nutrient management using Rice Crop Manager decision support tool in Odisha, India. *Field Crop. Res.* **2019**, *241*, 107578. [\[CrossRef\]](#)
- Yin, J.; Zhao, Z.; Lei, C.; Yang, S.X. Improved optical-type measurement method of grain flow using array near-infrared photoelectric sensors. *Comput. Electron. Agric.* **2021**, *183*, 106075. [\[CrossRef\]](#)
- Elsoragaby, S.; Yahya, A.; Mahadi, M.R.; Nawi, N.M.; Mairghany, M. Comparative field performances between conventional combine and mid-size combine in wetland rice cultivation. *Heliyon* **2019**, *5*, e01427. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zhang, W.; Hu, L.; Ding, F.; Luo, X.; Zhang, Z.; Hu, L.; Huang, P.; Peng, M. Parking precise alignment control and cotransporter system for rice harvester and transporter. *Comput. Electron. Agric.* **2023**, *215*, 108443. [\[CrossRef\]](#)
- Arslan, S.; Colvin, T.S. Grain yield mapping: Yield sensing, yield reconstruction, and errors. *Precis. Agric.* **2002**, *3*, 135–154. [\[CrossRef\]](#)

9. Shoji, K.; Itoh, H.; Kawamura, T. In-situ non-linear calibration of grain-yield sensor: Optimization of parameters for flow rate of grain vs. Force on the sensor. *Eng. Agric. Environ. Food* **2009**, *2*, 78–82. [\[CrossRef\]](#)
10. Reinke, R.; Dankowicz, H.; Phelan, J.; Kang, W. A dynamic grain flow model for a mass flow yield sensor on a combine. *Precis. Agric.* **2011**, *12*, 732–749. [\[CrossRef\]](#)
11. Chen, S.; Chou, H.; Li, Y.; Lu, Q. Design and experiment of test-bed for grain flow sensor. *Trans. Chin. Soc. Agric. Eng.* **2012**, *28*, 41–46. [\[CrossRef\]](#)
12. Chou, H.; Chen, S.; Zhang, L. Design and Test of Cereal Production, Intelligent Yield Monitor. *J. Agric. Mech. Res.* **2013**, *35*, 130–133. [\[CrossRef\]](#)
13. Xiong, Y.; Zhou, J.; Wei, W.; Shen, M.; Zhang, B. Design and experiment of grain mass flow sensor based on embedded system. *Trans. Chin. Soc. Agric. Eng.* **2018**, *34*, 39. [\[CrossRef\]](#)
14. Zhao, Z.; Lei, C.; Li, H.; Liu, J. Grain Thickness Sensor for Combine Harvester Grain Flow Measurement Based on Near-infrared Spectroscopy. *Trans. Chin. Soc. Agric. Mach.* **2019**, *50*, 6. [\[CrossRef\]](#)
15. Fu, X.; Zhang, Z.; An, X.; Zhao, C.; Li, C.; Yu, J. Development and performance experiment on grain yield monitoring system of combine harvester based on photoelectric diffuse reflectance. *Trans. Chin. Soc. Agric. Eng.* **2017**, *33*, 7. [\[CrossRef\]](#)
16. Maertens, K.; Reyns, P.; De Baerdemaeker, J. Double adaptive notch filter for mechanical grain flow sensors. *J. Sound Vib.* **2003**, *266*, 645–654. [\[CrossRef\]](#)
17. Jones, S.B.; Sheng, W.; Or, D. Dielectric measurement of agricultural grain moisture—Theory and applications. *Sensors* **2022**, *22*, 2083. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Warzecha, M.; Michalczyk, J. Calculation of maximal collision force in kinematic chains based on collision force impulse. *J. Theor. Appl. Mech.* **2020**, *58*, 339–349. [\[CrossRef\]](#)
19. Li, H.; Meng, C.; Zhao, Y. Automatic Expansion of Voltage Signals Using Empirical Mode Decomposition for Voltage Sag Detection. *IEEE Access* **2022**, *10*, 80138–80150. [\[CrossRef\]](#)
20. Yin, J.; Chen, Z.; Liu, C.; Zhou, M.; Liu, L. Design and Experiments of a Real-Time Bale Density Monitoring System Based on Dynamic Weighing. *Sensors* **2023**, *23*, 1778. [\[CrossRef\]](#)
21. Chen, Z.; Yin, J.; Yang, J.; Zhou, M.; Wang, X.; Farhan, S.M. Development and Experiment of an Innovative Row-Controlled Device for Residual Film Collector to Drive Autonomously along the Ridge. *Sensors* **2023**, *23*, 8484. [\[CrossRef\]](#)
22. Qarallah, B.; Shoji, K.; Kawamura, T. Development of a yield sensor for measuring individual weights of onion bulbs. *Biosyst. Eng.* **2008**, *100*, 511–515. [\[CrossRef\]](#)
23. Zhou, J.; Liu, C. Signal processing method for impact-based grain mass flow sensor with parallel beam load cell. *Trans. Chin. Soc. Agric. Eng.* **2008**, *24*, 5. [\[CrossRef\]](#)

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