DETECTION SYSTEM FOR FEEDING QUANTITY OF MOBILE STRAW GRANULATOR BASED ON POWER OF SCREW CONVEYOR

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基于螺旋输送器功率的移动式秸秆制粒机喂入量检测系统

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***Keywords:** straw granulator, power measurement, screw conveyor, feeding quantity, butterworth filter*

ABSTRACT

At present, straw harvesting operation is performed according to artificial experience, and there is no scientific method to detect the feeding quantity of the mobile straw granulator. This paper designed a feeding quantity detection system based on the power of the motive power shaft of the screw conveyor of the mobile straw granulator. The detection system includes the detection device and the detection method. The detection device consists of torque sensor, rotation speed sensor and on-board industrial computer. The detection method obtains the feeding quantity with the power that can be computed according to torque and rotation speed. The detection system was evaluated on the mobile straw granulator of Liaoning Ningyue agricultural machinery company. The field experiment shows that the average error of feeding quantity detection system is 7.5%, and the detection accuracy can meet the actual needs of the field application.

摘要

目前，秸秆收获作业靠人工经验判断，没有科学的方法来检测移动式秸秆制粒机的喂入量，本文设计了基于移动式秸秆制粒机螺旋输送器动力轴功率的喂入量检测系统。喂入量检测系统包括喂入量检测装置和喂入量检测方法。喂入量检测装置由扭矩传感器、转速传感器、车载工控机构成；喂入量检测方法中使用功率预测秸秆喂入量，功率通过扭矩与转速间接求取；本文以辽宁宁越农机公司的移动式秸秆制粒机为试验平台对检测系统进行了验证。田间试验表明，采用喂入量检测方法的平均误差为7.5%，检测精度能够满足实际田间应用需求。

INTRODUCTION

China is rich in all kinds of crop straw resources, of which the annual yield of corn straw can reach 180 million tons *(Zhao et al, 2019)*. Mechanized harvesting of corn straw in the field is very important, and the feeding quantity, as an important parameter in harvesting operation, determines the efficiency of corn straw harvesting. If the feeding quantity is too large, the key parts of the mobile straw granulator will be blocked. If the feeding quantity is too small, the harvesting efficiency of corn straw will be seriously restricted. How to use modern information technology to detect feeding of mobile straw granulator and improve the harvest efficiency is particularly urgent.

There have been many important theoretical results in the research on the feeding quantity of the mechanical equipment. According to the working principle of combine harvester, relevant scholars put forward the feeding quantity detection model and designed the feeding quantity detection system *(Savoie, et al, 2014)*. For example, the torque of the driving shaft and fuzzy neural network technology are used to detect the feeding quantity and adjust the speed of the combine harvester respectively *(Ji, 2005)*. A monitoring method to detect the feeding quantity of peanut was proposed based on the torque of the power input shaft of the pickup platform *(Wang et al, 2019)*. Through the dynamic analysis of the pickup, the mathematical model of the peanut harvester pickup is designed according to the torque and feeding quantity of the power input shaft of the peanut harvester pickup. The relationship between the feeding quantity of the combine harvester and the loss rate of the harvesting process was analysed to establish the mathematical model of them *(Siemens and Hulick, 2008)*. However, there are many factors that affect the change of feeding quantity, and the actual working environment is complicate, which lead to a large measurement error. And, these researches are mostly aiming at combine harvesters. Hence, the detection of feeding quantity of the mobile straw granulator is an urgent demand.

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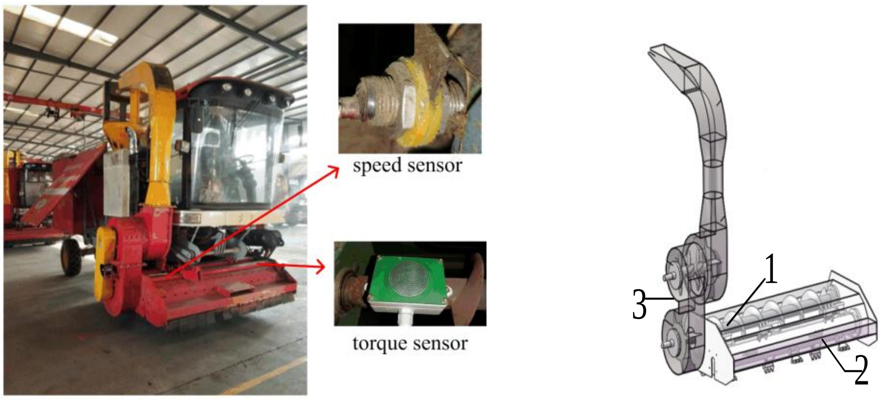
This paper proposed an embedded feeding quantity detection system. The relationship between the screw conveyor and the feeding quantity of the mobile straw granulator is analysed to build the correlation model. The embedded hardware system was constructed based on the STM32 and ZigBee, and had a low power consumption and high communication efficiency.

MATERIALS AND METHODS

Feeding quantity detection system

The mobile straw granulator is shown in Fig.1 (a), and the specific feeding device is shown in Fig.1 (b). During the harvesting of the mobile straw granulator, the corn straw is crushed and picked up by the front-end pickup device, and then the straw is sent to the screw conveyor. Then, the material is fed into the straw conveying equipment through the screw conveyor. Finally, the material enters the straw granulator silo.

This paper analysed the screw conveyor power shaft to establish the mathematical model between the power of the power shaft and the feeding quantity of the mobile straw granulator to detect the feeding quantity. The system includes detection device and detection method. As an important parameter of the mobile straw granulator, power can not only detect the feed quantity, but also reflect the power required by the straw granulator in the harvesting process. The detection of power parameters is significant to the detection system.



a. Test equipment *b. Structure diagram of feeding device*

Fig. 1 - Mobile straw granulator

1. Screw conveyor; 2. Picking up and crushing equipment; 3. Conveying equipment

Detection device

The detection system includes torque sensor, speed sensor and the on-board industrial computer. The overall scheme of the detection system is shown in Fig. 2. The on-board industrial computer is composed of microcontrollers, CAN (Controller Area Network) controller *(Harmon et al, 2018)*, display module, ZigBee RF (Radio Frequency) module *(Partal et al, 2019)* and 4G data transmission module. The speed sensor and the on-board industrial computer vehicle terminal adopt CAN bus protocol. Torsion sensor and on-board industrial computer communicate through ZigBee RF module; 4G data transmission module provides remote control interface. ZigBee RF module has advantages of low power consumption *(Bihl et al, 2017)*, Ad-hoc network *(Amer et al, 2020)* and stable communication, so ZigBee communication is used in the torque sensor communication module.

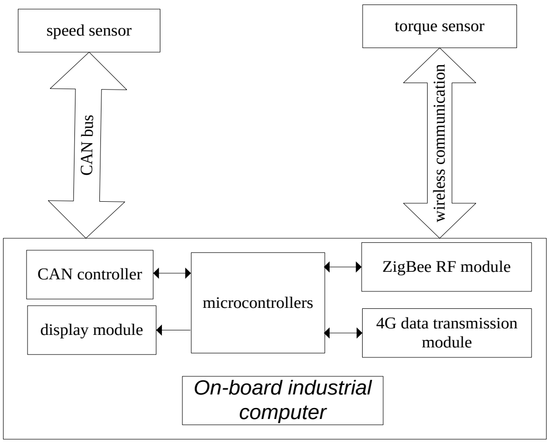


Fig. 2 – The detection system

The torque sensor which is used to detect the torque is shown in Fig. 3. Lithium battery with voltage of 3.7V and capacity of 3000mAh is used for power supply. The hardware circuit is shown in Figure 4. And the torque sensor was mounted on the mobile straw granulator as Fig. 1(a). Low-power chip stm32f030f4p6 is the core of data acquisition. ZigBee module which uses CC2530 RF with 2400Mhz as the working frequency is used to communicate information. The strain bridge (R8, R9, R2, R16) is used to generate voltage signal *(Feng and Wang, 2020)*. After being amplified by differential operational amplifier (U1B: lm358), buffered and isolated by voltage follower (U1A: lm358), voltage signal is sent to the fifth-order Butterworth low-pass filter composed of LM324 (U2A, U2B, U2C). The filter has the function of gain adjustment and filtering high-frequency signal *(Mahata et al, 2020)*. The parameters of resistance and capacitance in the filter are calculated according to the cut-off frequency and quality factor in the normalization table of low-pass filter. The frequency response curve is shown in Fig. 5. After the process of the filter, the required low-frequency signal is retained while the high-frequency signal generated by vibration is filtered out. With these components, the strain gauge deformation is converted into the voltage signal corresponding to the transmission shaft torque, and the voltage signal is converted into torque value. The single chip microcomputer sends the torque value to the ZigBee module (U4) through the pins (P0.2, P0.3). Then, the ZigBee module transmits the torsion value to the on-board industrial computer in the cab of the harvester through the spring antenna.

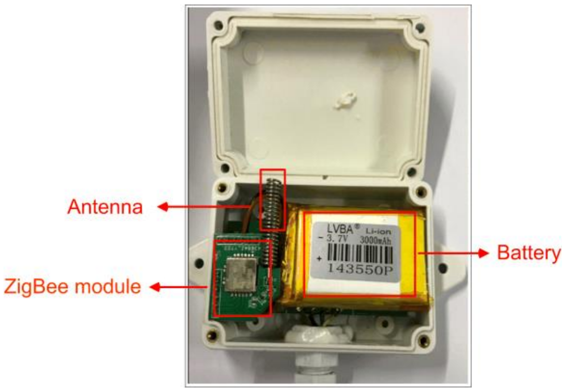


Fig. 3 – Torque sensor communication module

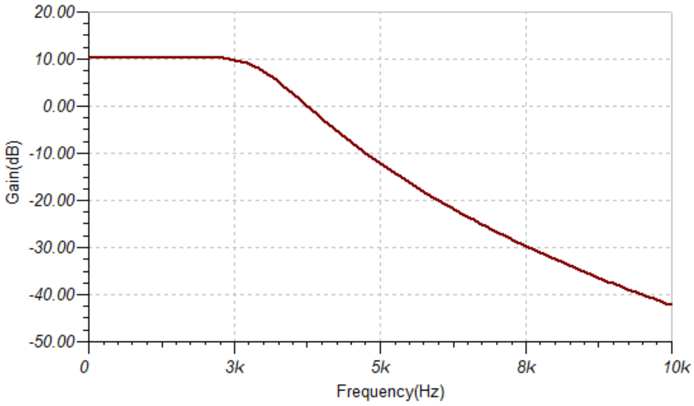


Fig. 5 –Frequency response curve of filter

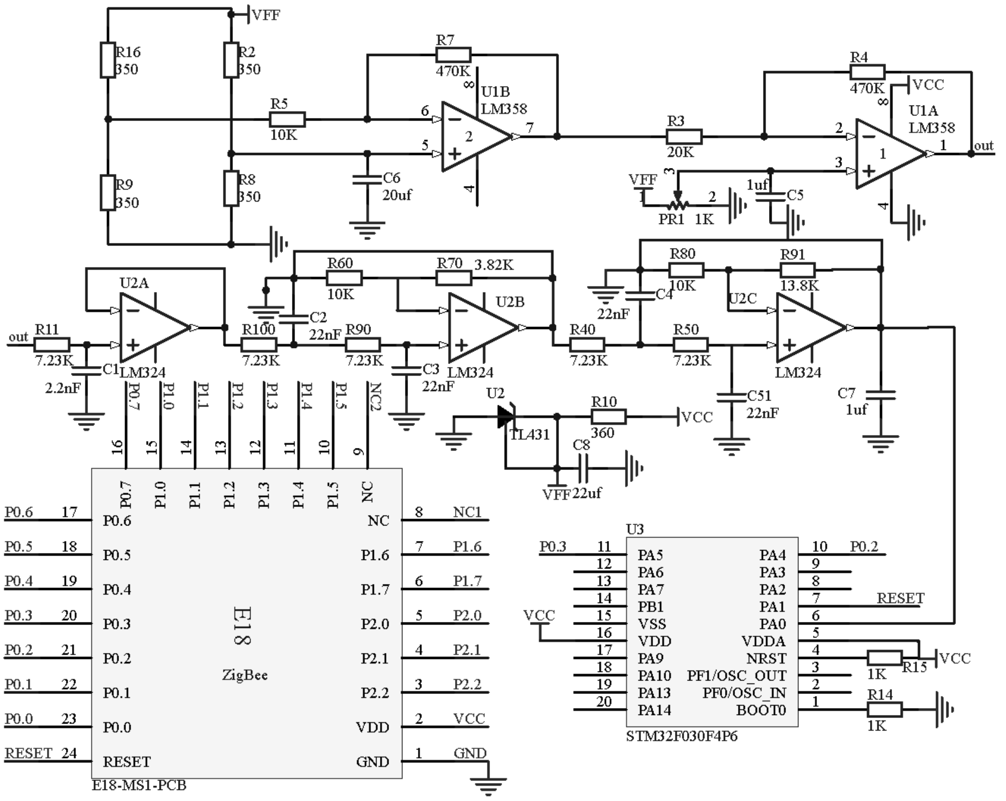


Fig. 4 – Hardware circuit of torque sensor

The on-board industrial computer device and the specific circuit are shown in Figure 6 and Figure 7, respectively.

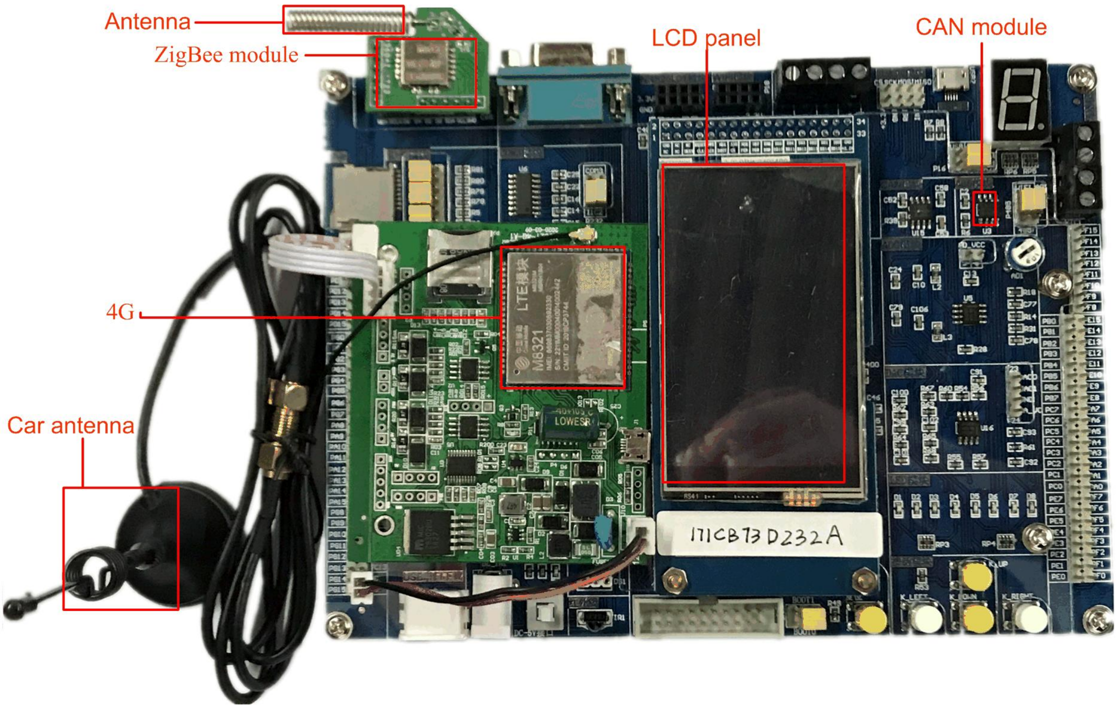


Fig. 6 – On board industrial computer

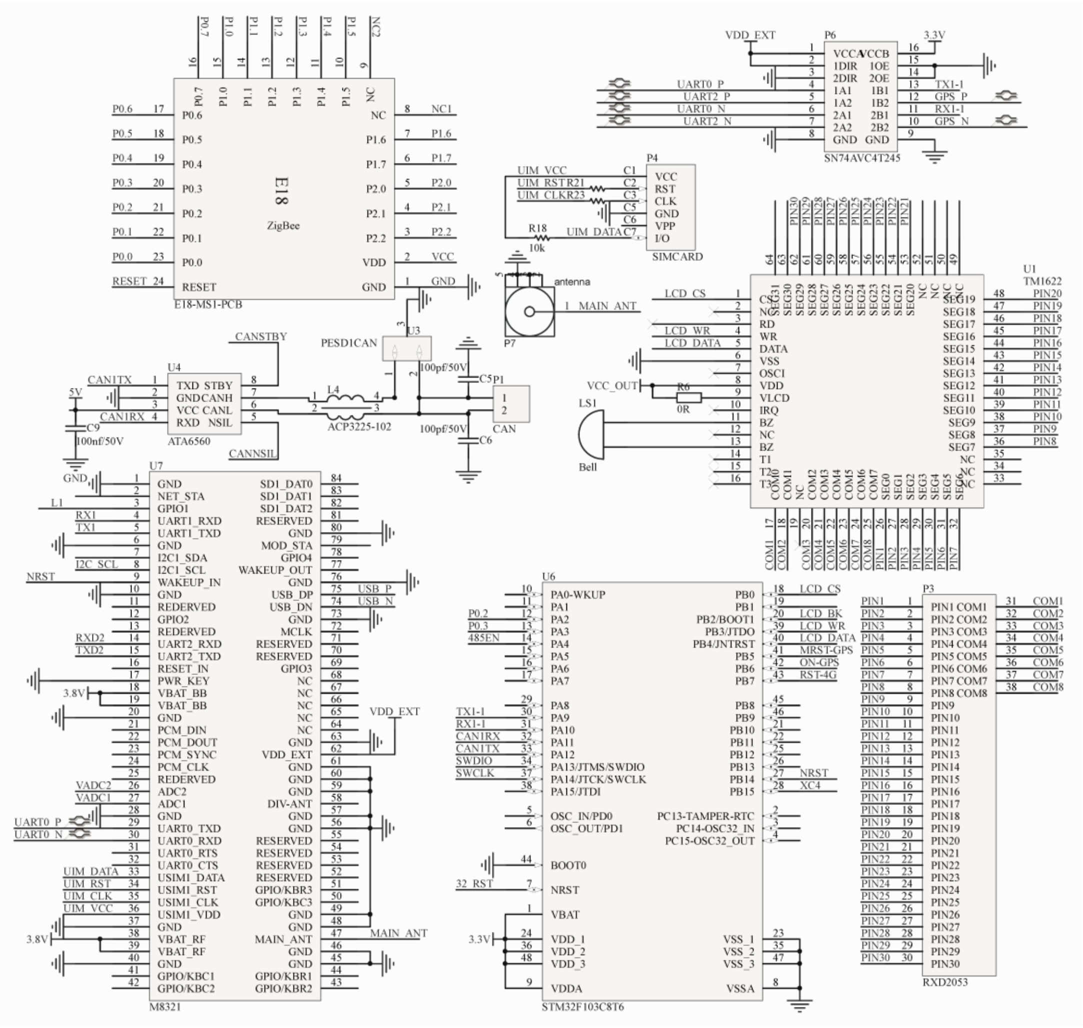


Fig. 7 – Circuit diagram of on-board industrial computer

When communicating with torque sensor, U6 (stm32f103c8t6) transmits command information to ZigBee module by USART communication through pins (P0.2, P0.3). Then, it is sent to the torque sensor. The on-board industrial computer communicates with the speed sensor through CAN controller U4 (ata6560). The capacitor C9 can filter out the high frequency interference of power supply. In order to improve the anti-electromagnetic interference ability of CAN bus interface, the anti-interference circuit is designed. U3 (PESD1CAN) is used to eliminate electrostatic interference. Transient power of U3 between 8 and 20us can reach 200W. The common mode filter L4 (WCM-3216-222T) can resist common mode interference. P3 (LCD) is driven by special driver chip U1 (TM1622) to display information such as torque, speed, power and feeding quantity. When the straw granulator is working, the microcontroller communicates with the 4G chip U7 (M8321); U7 interacts with SIM card P4, and the parameters related to the feeding quantity are transmitted to the background server by the antenna P7. P6 (SN74AVC4T245) is used to match the level of USART signal.

Detection method

In the detection of the feeding quantity, the power cannot be measured directly as there is no measuring equipment for agricultural machinery used in field operation. The power is related to speed and torque, so it is necessary to calculate the speed and torque of screw conveyor and measure the power indirectly. The voltage signal of the strain gauge can be collected by the electronic circuit, and the torque value corresponding to the voltage signal can be calibrated by the professional torque sensor. The speed is obtained by the speed sensor. The feeding quantity can be predicted by fitting the above power with the actual feeding value.

Power detection

The strain method is used for torque detection. As shown in Fig. 8, the main plane is the grey square whose perpendicular is 45 degrees relative to the X axis. σ_1 and σ_2 represent tensile stress and compressive stress, respectively. And they are equal in value. According to Hooke's law *(Kaanta et al, 2018)*, the tensile strain and compressive strain along the principal stress direction are expressed as Eq. (1) and (2), respectively.

$$\varepsilon_{45^\circ} = \varepsilon_1 = \frac{\sigma_1}{E} - \mu\frac{\sigma_2}{E} = (1+\mu)\frac{\sigma_1}{E} = \frac{16(1+\mu)}{\pi E D^3} \tag{1}$$

$$\varepsilon_{-45^\circ} = \varepsilon_2 = \frac{\sigma_2}{E} - \mu\frac{\sigma_1}{E} = (1+\mu)\frac{\sigma_2}{E} = -\frac{16(1+\mu)}{\pi E D^3} \tag{2}$$

In the above expression, E denotes the elastic modulus of the material and μ is the Poisson's ratio of the material. Under the influence of torque, the strain in the direction of plus or minus 45 degrees is equal and the direction is opposite. If $\varepsilon_{45^\circ} = \varepsilon_{-45^\circ} = \varepsilon\left(\varepsilon > 0\right)$, the torque can be obtained by Eq. (3), in which, $G=E$ $(2(1+\mu))$ is the shear modulus, $\gamma=2\varepsilon$ is the shear strain, and D is the outer diameter of the drive shaft.

$$T_1 = \frac{\pi D^3}{16} G\gamma \tag{3}$$

Therefore, the torque of the shaft can be obtained by applying strain gauges on the axial direction of plus or minus 45 degrees and the torque of the shaft $T_1(\varepsilon)$ can be obtained by detecting the maximum strain change of the transmission shaft. There is a linear relationship between T_1 and ε.

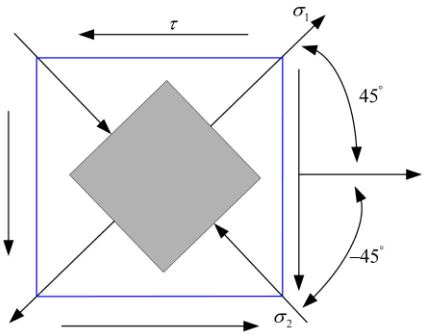


Fig. 8 – Schematic diagram of torque principle

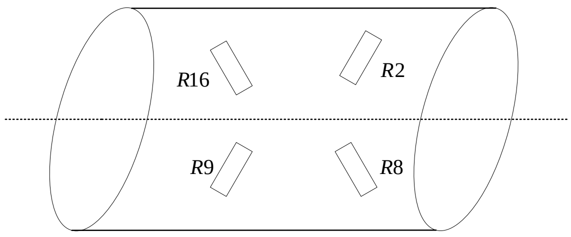


Fig. 9 – Schematic diagram of strain gauge mounting method

The mounting method of strain gauge of torque sensor is shown in Fig. 9. The torque sensor uses strain gauges to form Huygens bridge, and four strain gauges (R_8, R_9, R_2, R_{16}) form an equal arm full bridge, and they form an angle of 90 degrees respectively. When the transmission shaft is strained by torque, the resistance value of the strain gauge changes with the surface stress of the driving shaft. And this leads to the change of the output voltage. Through the calibration and measurement of the output voltage signal, the torque T_1 of the driving shaft of the screw conveyor can be obtained. The speed sensor is designed according to Hall Effect *(Kumar and Ganguli, 2020)*. It was mounted on the mobile straw granulator as shown in Fig. 1(a). The magnetic steel is pasted on the side of the driving wheel of the screw conveyor. When the magnetic steel passes through the hall element, the Hall Effect will be generated to form a pulse signal. The rotational speed denoted by n_1 of the driving shaft of the screw conveyor is calculated according to the number of pulses recorded in unit time multiplied by 60 seconds. By detecting the torque T_1 and speed n_1 of the driving shaft of the screw conveyor, the power P of the driving shaft is calculated, as shown in Eq. (4).

$$P = (n_1 * T_1) / 9559 \tag{4}$$

Calculation of actual feeding quantity

The actual feeding quantity is related to the moisture content of straw, the picking width of straw granulator, the height of screw conveyor and its walking speed. The density of straw in the test plot was uniform, and the moisture content was basically the same at harvest. The actual feeding quantity q could be obtained by calculating the weight m of straw per unit area and the area S of straw picked up by the straw granulator in unit time. The area S of straw harvested in unit time can be calculated by walking speed v of straw granulator and width d of the straw. In the working process of the straw granulator, if the picking width and the height of screw conveyor remain unchanged, the walking speed and the quantity of straw per unit area become the main factors affecting the feed quantity. The calculation of the actual feeding quantity is shown in Eq. (5), in which, q represents the actual feeding quantity, S represents the straw area per unit time, d is the actual picking width at harvest, v denotes the walking speed of straw granulator, and m denotes the mass of the straw per unit area.

$$q = Sm = dvm \tag{5}$$

RESULTS AND DISCUSSION

Field experiment and verification of straw granulator

The power and feeding quantity were obtained by experiments. The relationship between the predicted feeding quantity and the measuring power was obtained by linear model fitting. In order to verify the effectiveness of the power measurement method, it is necessary to verify and compare the feeding quantity predicted by power with the actual feeding quantity through field test.

Test conditions and methods

In order to establish the prediction model of screw conveyor power, straw harvest simulation experiment was conducted in Liaoning Ningyue Agricultural Machinery Co., Ltd. Xiaguang 560xg type straw granulator was used, and the on-board industrial computer device was installed in the cab. In this experiment, the moisture content of straw was the same, the length of rectangular crushed straw was 10 meters, the width was 2.0 meters, and the weight of unit straw was 1 kg. The pickup device and screw conveyor were 10cm above the ground. The frequency of data frame transmitted by ZigBee wireless communication was set to 400 Hz.

Test data processing and analysis

The accuracy of torque measurement is very important in this detection system. In this paper, the single chip microcomputer is used to collect the deformation signal. Before collecting the deformation signal, the hardware circuit of the fifth-order Butterworth filter *(Mahata et al, 2020)* is used to pass the noises. The function of the filter is verified by experiments.

Fig.10 shows the voltage waveform collected without Butterworth filter. It can be seen from the figure that there is more noise. The signal error range is large and it will affect the stability of the whole detection system.

The signal processing curve of Butterworth filter is shown in Fig.11 with less noise signal and stable voltage signal.

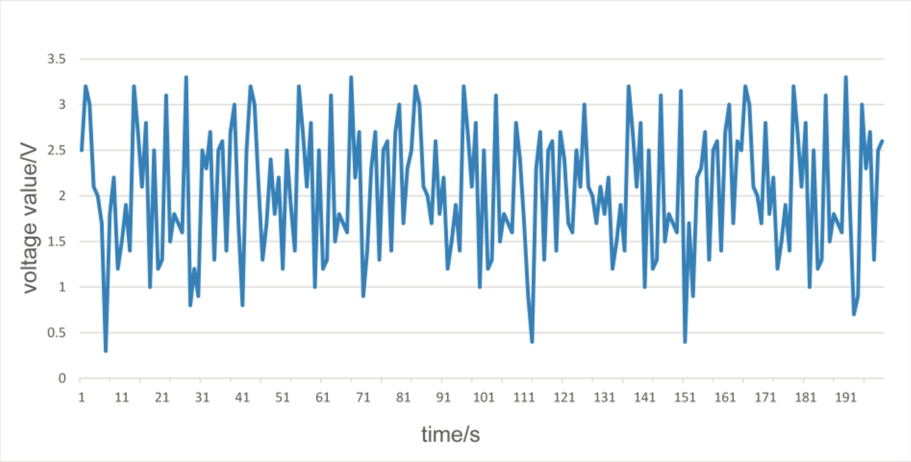


Fig. 10 – Voltage curve before noise filtering

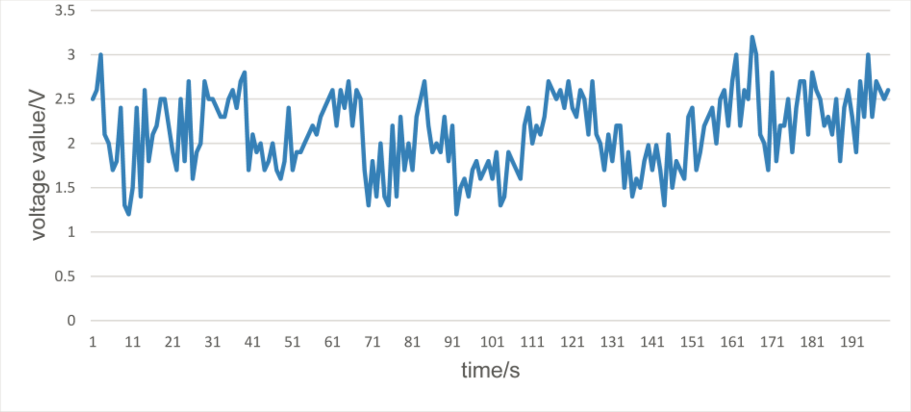


Fig. 11 – Voltage curve after noise filtering

The A/D module of single chip microcomputer collects the voltage signal value which is converted into torque value after arithmetic average filtering algorithm in software. The specific calibration data is shown in Table 1, and the calibration Eq. (6) can be obtained from the calibrated data.

$$y = 47.6x - 57.2 \tag{6}$$

Table 1

Torque sensor calibration test data

Torque (N.m)	Measured mean voltage (V)	Theoretical voltage (V)	Voltage prediction error (V)
0	1.202	1.202	0
25	1.718	1.728	0.011
50	2.260	2.252	0.008
75	2.791	2.777	0.014
100	3.291	3.300	0.009

The torque value detected by the calibrated torque sensor is shown in the second column of Table 2. The power of screw conveyor obtained by Eq. (4) through speed and torque is shown in the fourth column of Table 2. The actual feeding quantity is calculated by Eq. (5), as shown in the fifth column of Table 2.

According to table 2, the on-line monitoring power data of screw conveyor and the feeding data are linearly fitted. The fitted regression curve is shown in figure (12), and the correlation coefficient is 0.964.

The fitted linear model is shown in Eq. (7).

$$y = 0.2139x - 0.435 \tag{7}$$

Table 2

Test data obtained by online monitoring system

Speed of screw conveyor (r/min)	Torque (N.m)	Vehicle speed (m/s)	Power of screw conveyor (kW)	Feeding quantity (kg/s)
1406	48.9	0.5435	7.196	1.087
1423	48.6	0.5595	7.245	1.119
1456	48.1	0.5680	7.328	1.136
1487	48.0	0.5985	7.482	1.197
1489	48.4	0.6050	7.543	1.210
1510	48.1	0.5855	7.601	1.171
1534	48.6	0.5975	7.807	1.195
1544	49.5	0.6605	7.993	1.321
1564	50.1	0.6620	8.208	1.324
1585	50.1	0.6685	8.308	1.337
1596	50.5	0.6730	8.442	1.346
1601	51.3	0.6840	8.565	1.368
1608	51.2	0.6835	8.612	1.367
1600	52.0	0.7035	8.712	1.407
1599	52.8	0.7365	8.812	1.473
1612	54.8	0.7445	9.233	1.489
1605	53.3	0.7535	8.945	1.507
1612	53.7	0.7625	9.064	1.525
1590	55.1	0.7780	9.165	1.556
1589	55.8	0.7890	9.283	1.578

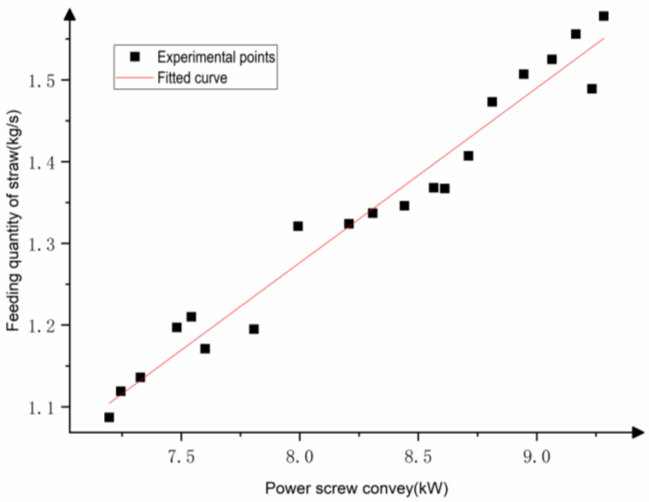


Fig. 12 – Regression curve after fitting

Field experiment

After the establishment of the model, the actual harvest experiment was carried out in the field, as shown in Fig. 13. Some experimental data are shown in Table 3. The mean error is equal to 7.5%. The measured value and the actual value of the feeding quantity are in the acceptable range. In conclusion, there is a linear relationship between the power of screw conveyor of straw granulator and the feeding quantity, and the feeding quantity can be predicted by power. The feeding quantity detection method based on power measurement proposed in this paper is effective. It can be used in the mobile straw granulator which integrates crushing, picking up and briquetting. It provides a method for the automatic control of the mobile straw granulator.

Fig. 13 –Field experiment

Table 3

Field test monitoring data

Power of screw conveyor (kW)	Calculated feed quantity (kg)	Actual feeding quantity (kg)	Error (%)
7.056	1.074	1.174	-8.5%
7.189	1.013	1.123	-9.7%
7.213	1.108	1.091	1.5%
7.402	1.148	1.099	4.4%
7.489	1.167	1.237	-5.6%
7.672	1.206	1.123	7.3%
7.834	1.241	1.356	-8.4%
7.939	1.263	1.316	-4.0%
7.589	1.188	1.099	8.0%
8.103	1.298	1.123	15.6%
8.246	1.329	1.298	2.3%
8.465	1.376	1.452	5.2%
8.378	1.357	1.278	6.1%
7.982	1.272	1.367	6.9%
7.843	1.243	1.146	8.5%
8.726	1.431	1.278	12.0%
8.894	1.467	1.325	10.7%
9.046	1.500	1.423	5.4%
8.905	1.415	1.612	12.2%
9.248	1.543	1.432	7.7%
Average error			7.5%

CONCLUSIONS

This paper proposed a system to detect the feeding quantity of the mobile straw granulator. The contributions are mainly embodied in three aspects:

(1) The linear relationship model between the screw conveyor and the feeding quantity was established. And the effectiveness of the model has been verified in the field experiment. It showed that predicting the feeding quantity by the power of the screw conveyor is feasible.

(2) The detection device including data acquisition, Butterworth filter, torque sensor, communization module, and control module was designed. It has the advantages of low power consumption and high signal noise ratio.

(3) The circuit of the main detection device was described in the paper. The scheme of this paper can be duplicated according to the circuit and the descriptions of the system.

Due to the bad working environment of straw crushing and picking up, in the future work, it is necessary to further study the methods to improve the working stability of strain gauge, such as improving materials, improving installation methods and other measures to further improve the detection accuracy.

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