TECHNOLOGY OF ADJUSTING THE HEADER HEIGHT OF THE HARVESTER BY MULTI-SENSOR DATA FUSION BASED ON BP NEURAL NETWORK
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基于 BP 神经网络的多传感器数据融合调节收割机割台高度

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DOI: https://doi.org/10.35633/inmateh-68-09

Keywords: *BP neural network, fuzzy control, cutting platform height, multisensor*

ABSTRACT
In this paper, BP neural network is used to collect header height, AMEsim is used to simulate and analyze header height adjustment hydraulic system, and fuzzy PID control is used to adjust header lifting hydraulic cylinder to stabilize header height. The experimental results of harvesting different crops show that under the header height automatic control system, the error between the actual height of crop harvesting and the set height is within 15 mm, and the harvesting effect is good, which can meet the automatic regulation requirements of the header height of the multi crop combine harvester.

摘要
为了提高调节的精度，采用 BP 神经网络多传感器融合处理技术采集割台实时高度，通过 AMEsim 软件对割台高度调节液压系统进行仿真分析，最后采用模糊 PID 控制比例电磁阀调节割台升降液压缸从而稳定割台高度。通过收获油菜、谷子和水稻的试验结果证明：在割台高度自动控制系统下，作物收获的实际高度与设定高度误差在 15mm 以内，收获效果较好，作物割茬高度较为平整，满足多作物联合收获机割台高度自动调控需求。

INTRODUCTION
In the process of multi-crop harvesting, the height of the header is one of the important parameters. If the height of the header is adjusted too large, only part of the plants will be harvested, which may increase the amount of crop loss; if the height of the header is adjusted too small, the straw of harvested grain is too long and may cause the header to clog up or touch the ground, affecting the performance of the harvester. In order to ensure that the height of the header is stable during the harvesting process and reduce the labor intensity of the operator, domestic and foreign engineers and scholars have done relevant researches on the height control of the harvester header *(Tao et al, 2018; Liu et al, 2014; Zheng et al, 2015).*

Hunan Agricultural University *(Liao et al., 2018)* proposed a crop height detection device based on unilateral infrared reflection and a strategy based on fuzzy PID control algorithm to control the height of the header, and used the designed device and system to take rice as the research object. *Yang et al, (2022*), designed an adaptive header height control system. The limitation of traditional PID facing the integral saturation state is analyzed, and a new EVPIVSPID algorithm is proposed and simulated.

Aiming at the problem of low harvesting efficiency caused by the adjustment of the header mainly relying on the experience of the operator when the existing combine harvesters in China are harvesting various crops, this paper designs an automatic control system for the height of the header, and establishes the hydraulic pressure of the multi-crop combine harvester. The relationship model between the telescopic length of the cylinder and the height measured by the sensor, and the collected signals are processed by the BP neural network multi-sensor fusion technology to reduce errors, and the height of the header is regulated by the fuzzy PID control algorithm, so as to be able to achieve cutting in a multi-crop field environment. The automatic control of the table height reduces labor intensity and improves work efficiency.

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MATERIALS AND METHODS

Design of the profiling device for height adjustment of the header

Fig.1 is a schematic diagram of the height measurement system of the header. The mechanical contact type header height measuring device is mainly composed of a left-right symmetrical profiling plate, a rotating shaft, an angle sensor, a single-chip microcomputer, etc. The structural schematic diagram is shown in Fig. 2:

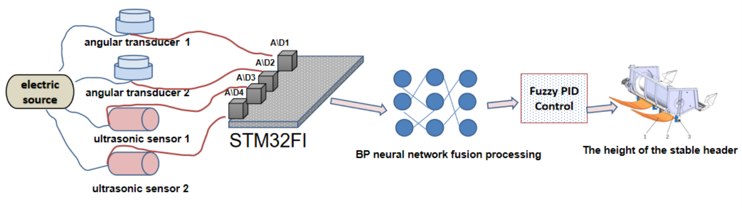

Fig. 1 - Schematic diagram of the header height measurement system

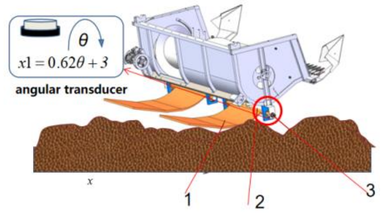

Fig. 2 - Structural Schematic
1. Copy plate; 2. Turn shaft; 3. Angle sensor

After calibration, the relationship between the measured header height *x*1, *x*2 [cm] and the rotation angle θ [°] of the two angle sensors is:

$$x1 = 0.62\ \theta + 3 \tag{1}$$

Non-contact measuring device

The CUM30-M2DV ultrasonic sensor is selected, and ADC3 and ADC4 are used for signal acquisition. The working schematic is shown in Figure 3.

Working principle: The ultrasonic signal is emitted by the ultrasonic transmitter, and the return signal is received by the receiver after the ultrasonic signal touches the ground. The time difference t1 is calculated by the timer function in the controller. Combined with the ultrasonic sound speed calculation formula, the header height K can be calculated:

$$V1 = 331.45 + 0.6T \tag{2}$$

T is the ambient temperature, [°C], which can be measured manually, or a temperature sensor can be installed to meet the time-varying requirements of temperature to reduce the error and obtain the height of the ultrasonic sensor above the ground:

$$K = V1 \times \frac{t1}{2} \tag{3}$$

Among them: K is the distance from the sensor to the field ground, [cm]; $V1$ is the propagation speed of ultrasonic, [cm/s] and $t1$ is the time difference from the transmitted signal to the received signal in seconds.

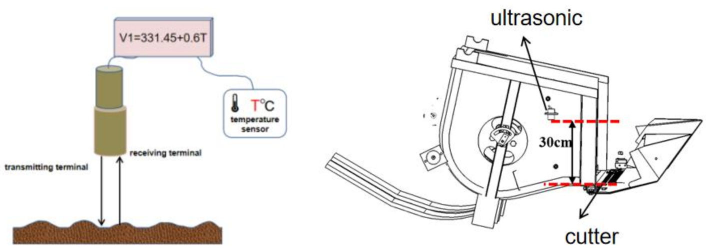

Fig. 3 - Work schematic diagram

Since the ultrasonic sensor is actually installed on both sides of the header, it measures the height of the ultrasonic wave from the ground, and the vertical distance between the ultrasonic wave and the cutting knife is $K0$, $K0$=30 cm, so the actual header height $x3$ and $x4$ obtained by the two ultrasonic measurements are:

$$x3 = K - K0 \tag{4}$$

Multi-sensor data fusion based on BP neural network to adjust the height of harvester header

This project intends to adopt a multi-sensor data fusion processing to adjust the harvester header height technology based on BP neural network. The neural network of the header control system is set as four input points and one output point, and a traditional three-layer network structure is shown in Fig 4 (*Guo et al, 2018; Wang et al, 2022; Qiu et al, 2018)*.

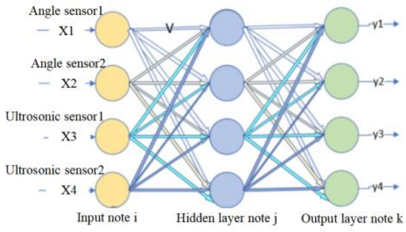

Fig. 4 - Neural network diagram of highly regulated system

The schematic diagram of the fusion processing method based on BP neural network is shown in Fig. 5.

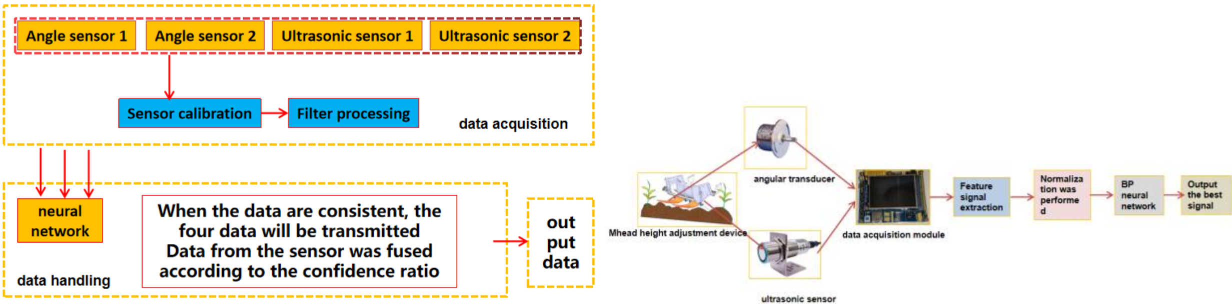

Fig. 5 - Schematic diagram of the fusion processing methods for multiple sensors

In order to obtain an ideal model for the height adjustment control system of the header, a large number of data acquisition and analysis were carried out. In MATLAB, according to the characteristics after filtering the measuring data of ultrasonic sensor and angle sensor, multiple pieces of collected data and multiple pieces of data to be fused at header heights of 10 cm are constructed, including two angle sensors and two ultrasonic sensors. Collect the height data of the header, and finally output the accurate measurement value of the height of the header.

Model establishment

The model of the header height control system is established by Matlab software, which can realize the functions of neural network and fuzzy reasoning (*Erzan et al., 2021)*. The toolbox in this software can realize self-learning of the system to obtain the output value by a lot of training on the established model. In this model, a fuzzy rule corresponding to the input ($x1$, $x2$, $x3$, $x4$) of the four sensors and the output f1 can be implemented. For the calculation from input to output, the intermediate layer is implemented, and the back-propagation algorithm is directly integrated into the inference process in order to obtain accurate output. The whole process can be divided into the following steps:

(1) Use the selected ultrasonic sensor and angle sensor to measure the height regulation state of the header;

(2) Preprocess the collected signals of the four sensors and perform signal feature selection;

(3) These characteristic signals are normalized, and finally the input model of the neural network of the header height control system is obtained. In this paper, the simple and practical Max-min normalization method is used to limit the data processing in the [0,1] interval. Its calculation formula is:

$$X= (x-xmin)/(xmax-xmin) \tag{5}$$

x represents the original value, X represents the converted standard value, and $xmin$ and $xmax$ represent the minimum and maximum values of x, respectively.

According to the performance indicators and coefficient calibration of the ultrasonic sensor and the angle sensor, the signals of the four sensors are collected and fused when the height of the header is 10 cm, respectively. The processing sample of BP neural network model in this paper selects the signal value collected when the header height is 10 cm, as shown in Table 1.

The height at 20 cm and 30 cm was also selected as the neural network fit, which was consistent with that at 10 cm, and it was not repeated again.

Table 1

Signal value of header height of 10 cm

Sample number for signal acquisition	1	2	3	4	5	6	7	8	9	10
Angle sensor 1, cm	9.9	10.3	10.1	10.4	9.7	9.8	10.2	9.6	10.0	10.1
Angle sensor 2, cm	10.2	9.9	10.0	10.3	9.6	10.4	10.1	10.2	10.4	9.6
Ultrasonic sensor 1, cm	10.4	10.2	9.7	9.6	10.3	10.5	9.8	10.4	9.4	10.4
Ultrasonic sensor 2, cm	10.3	10.0	10.1	9.8	10.5	9.7	9.9	10.4	10.3	9.6

Neural network model fitting in the header height control system

There are four input points and one output point in the neural network fusion processing of the height control of the header. The four input points represent four sensors. The data collected above are imported into the software for model fitting, and 70% of all data are selected as the training samples, 15% of the data is used as the verification sample, and 15% of the data is used as the test sample.

Fitting process and effect diagram are shown in Fig. 6.

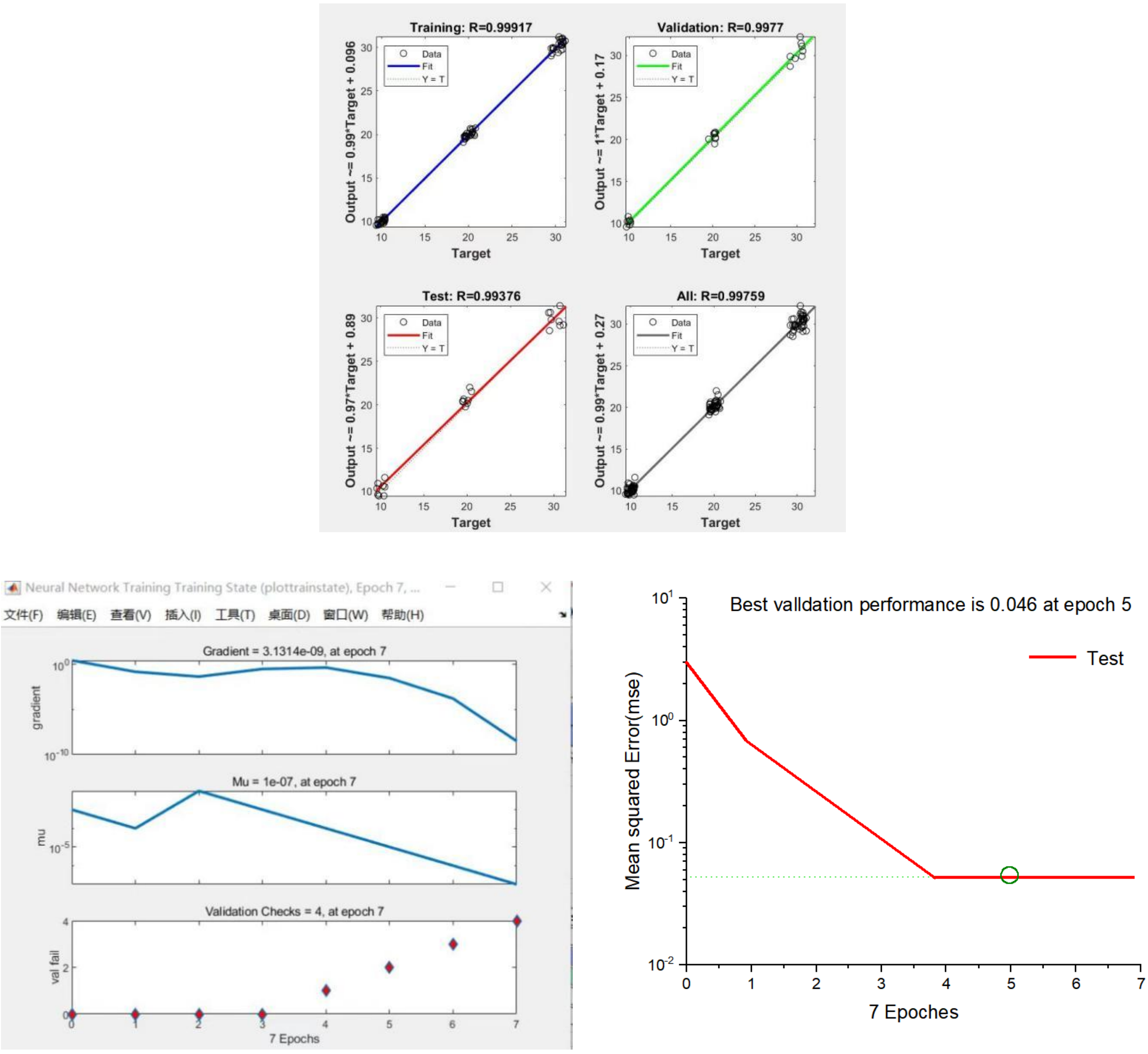

Fig. 6 - Fitting process and effect

The fitting process and effect chart show that the R value of the training sample is 0.99917, the R value of the validation sample is 0.9977, the R value of the test sample is 0.99376, and the overall R value is 0.99759, all of which are infinitely close to 1, indicating that the accuracy of the training model is good. From the BP neural network fitting training error curve, it can be seen that the error continues to decrease after iterative fusion processing, and the validation set and test set also have a good prediction effect, which reflects the BP neural network in adjusting the header.

The practicality of multi-data fusion processing in the height, the fitting error histogram is shown in Fig 7.

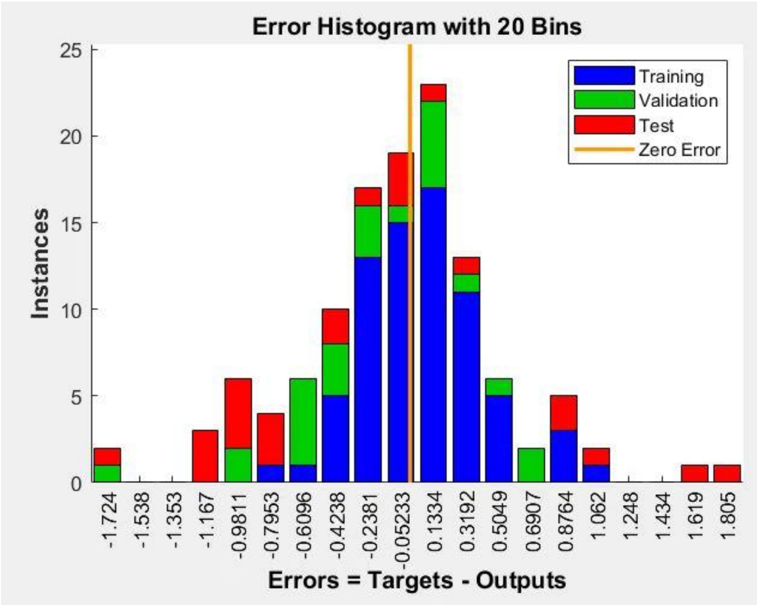

Fig. 7 - Model fit error plot

According to the above model fitting error diagram, the error range of the output results is between -1.742-1.805, and it is mainly concentrated between -0.6096-0.5049. The model training shows that the measured real-time height error range of the header meets the accuracy required.

Modeling and simulation of the hydraulic part of the header height control system using AMEsim software

The modified hydraulic system of the height of the header is simulated and analyzed. It is known that the initial position of the hydraulic cylinder of the header is about 1.5 cm. When the header is raised to the highest level, the displacement of the hydraulic cylinder is about 35 cm. The simulation model and results are shown in Fig. 8. The results show that the designed hydraulic system for the height of the header has a faster response speed, the header can be raised to the highest position within 10 s, and the accuracy is high, which indicates that the designed method is feasible.

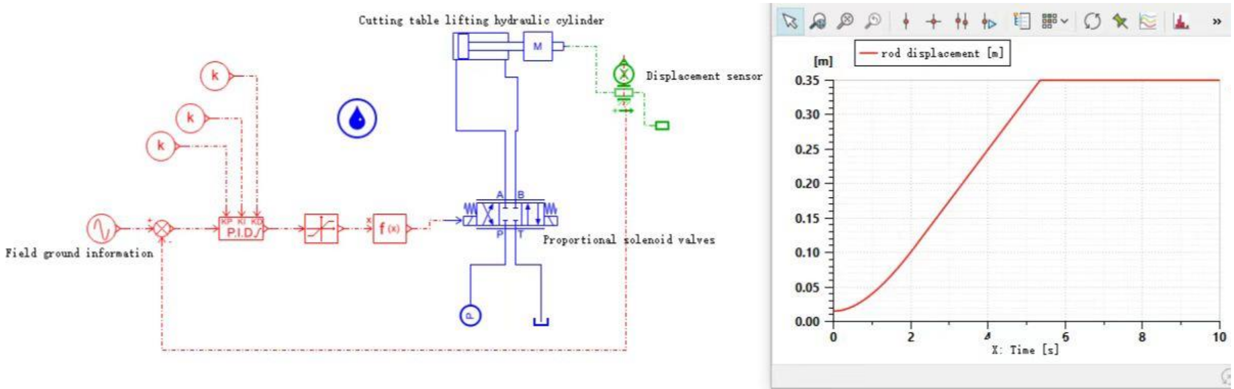

Fig. 8 - Simulation analysis and results of header height hydraulic system

Fuzzy PID design for automatic height adjustment system of multi-crop harvesting header

The real-time height of the header *x* is obtained through the multi-sensor fusion processing of the BP neural network above to obtain a relatively accurate value, and the deviation and deviation change rate are obtained by comparing with the height value of the set header for harvesting crops. In the process, the empirical value of the height of the header suitable for different crops and the reference to the relevant information determine the basic universe of input and output variables. The domain of discourse of E and EC is {-20, 20}, and the domain of discourse of the output variable u is {-5, 5}. It is corrected by fuzzy control theory. The fuzzy subsets of input and output variables are {PB, PS, ZR, NS, NB} *(Xia et al, 2015; Chen et al, 2015; Zhou et al, 2019)*. In order to simplify the calculation process, the membership functions of input distance deviation E and input distance change rate EC all use trigonometric functions. The schematic diagram is shown in Fig. 9:

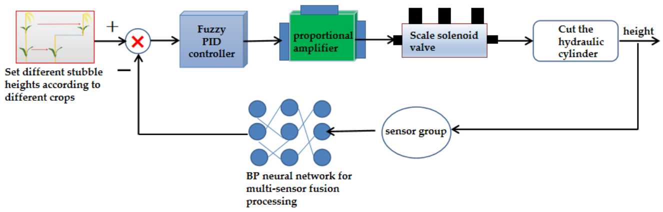

Fig. 9 - Schematic diagram of the header highly fuzzy PID control system

Determination of Header Height Control Transfer Function Model

Generally, in the application of agricultural machinery engineering, the proportional solenoid valve can be regarded as a second-order link, and its transfer function is:

$$\frac{Q(s)}{I(s)}=\frac{k_q k_1 \frac{1}{A_v}}{\frac{s^2}{\omega_h^{\ 2}}+\frac{2\xi_n s}{\omega_h}+1} \tag{6}$$

k_q is the flow gain of the electrohydraulic proportional valve m^3(S.A), k_q=8.66 × 10^{-4}, k1 is the displacement sensor magnification, k_1 = 9.5, A_v is the effective fluid dynamic area of the main slide valve core, $A_v = 1.06 \times 10^{-2}\ m^2$, ω_h is the natural frequency of the electrohydraulic proportional valve rad/s, take it at 9.5, and ξ_n is the electric-hydraulic proportional valve damping ratio take 6.58.

The transfer function of the proportional solenoid valve driving the hydraulic cylinder to control the height of the header is:

$$G_0(s)=\frac{183.96}{(s^2+25.02s+90.25)k} \tag{7}$$

k is a known constant, $k = \mathrm{x} + 2.65\cos(\beta + 32) - 0.753$. β is the initial angle between the conveyor tank and the vertical plane, and x is the lifting height of the header.

Use the graphical user interface in the Fuzzy Toolbox to create a fuzzy control model based on the fuzzy control strategy. In the membership function editor, set the membership function type, basic universe, and the number of fuzzy variable subsets (*Xia et al, 2015)*, as shown in Figure 10.

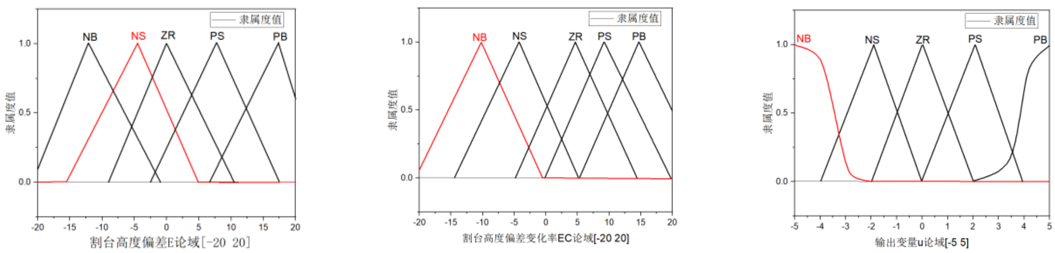

Fig. 10 - Header height, rate of change of height, and membership function plot of output variables

（a） E （b） EC （c）u

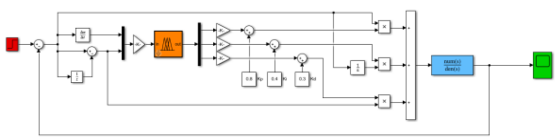

Fig. 11 - Simulation model of fuzzy control

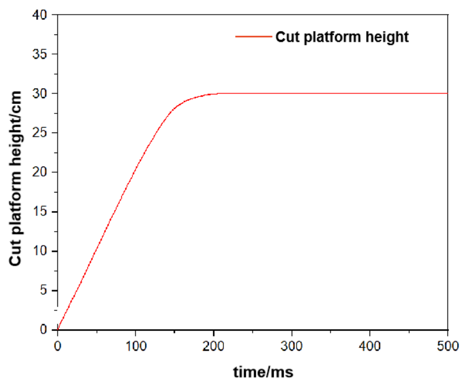

Fig. 12 - Analysis result curve

The simulation model of the fuzzy controller is built in the Matlab/Simulink software, as shown in Fig. 11. Set the simulation time to 0.5 s, simulate the control system, set Kp=0.8, ki=0.4, kd=0.3, and set the height of the header to 30 cm during simulation, that is, the steady-state value of the output of the PID controller is 30 cm, 0.4 s, it is stable and has a fast response speed, which can meet the design requirements of the automatic control system for the height of the header. The analysis results are shown in Fig. 12.

Design of header height data acquisition and output system

The master controller and slave device of the communication system use STM32F1 as the microcontroller. The slave device collects various analog signals or pulse signals through the microcontroller, converts them into digital signals, and sends them to the master controller through the RS485 bus. The overall framework of the RS485 system is shown in Fig. 13.

In 2021, rapeseed, soybean, and rice harvesting experiments will be carried out in Qinghai, Shandong, and Jiangsu, respectively. Due to the large differences in topography of the three fields, they can be used to test the performance of automatic height adjustment of the header. The test model is a 4LZ-5B multi-crop combine harvester, as shown in Fig. 14.

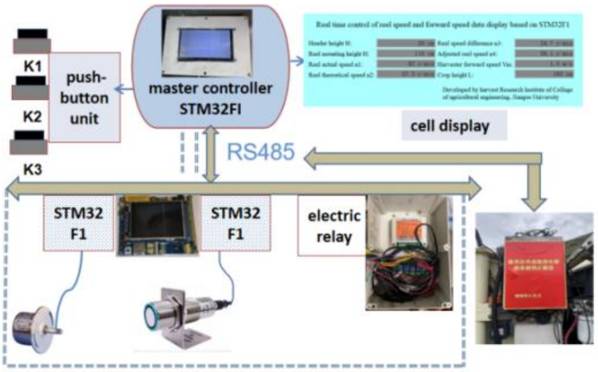

Fig. 13 - Overall framework of the R S 485 system

Fig. 14 - Header adjustment device diagram and test diagram

RESULTS

During the field test, the forward speed and direction of the harvester are controlled by the staff, and the height of the header is controlled by the automatic control system. The flagpole is used to set a stop measuring point every 10 meters to measure the height of the header, and the tester uses a tape measure to measure the height of the header from the ground. Table 2 shows the test results when harvesting rapeseed, millet and rice.

Table 2

Test results of combine header height control

test number	Set the height of the cutting table (Rape / Rice / millet) mm	Actual measurement height (Rapeseed / rice / millet) mm	bias in statistics (Rapeseed / rice / millet) mm
1	300/280/210	295.3/275.5/203.0	-4.7/-4.5/-7.0
2	300/280/210	304.8/286.8/212.5	4.8/6.8/2.5
3	300/280/210	296.8/279.5/205.9	-3.2/-0.5/-4.1
4	300/280/210	294.0/276.5/201.7	-6.0/-3.5/-8.3
5	300/280/210	310.6/291.6/217.5	10.6/11.6/7.5
6	300/280/210	295.2/277.3/204.5	-4.8/-2.7/-5.5
7	300/280/210	313.5/294.2/219.6	13.5/14.2/9.6
8	300/280/210	307.4/289.5/215.6	7.4/9.5/5.6

The test results show that when harvesting rape, the error of the height adjustment of the header is less than 13 mm; when harvesting millet, the error of the height adjustment of the header is less than 10 mm, the small error may be because the flatness of the field is high. In the case of rice, there may be many weeds in the field, which affect the accuracy of the sensor measurement, so it exceeds the error of the other two crops when harvesting, but the maximum error does not exceed 15 mm, which meets the harvesting requirements. Therefore, the designed header height control system in this paper can meet the field operation needs of the multi-crop combine harvester.

CONCLUSIONS

(1) Through the BP neural network multi-sensor fusion processing technology, the real-time acquisition value of the header height is obtained, which lays a foundation for the subsequent high-precision and low-error adjustment of the header height.

(2) Carry out the modeling analysis of the mechanical system and the hydraulic system of this harvester to obtain the open-loop transfer function of the header height with respect to the control current, and obtain the response curve of the fuzzy PID control system through Simulink simulation, and the results show that the control system has fast response time and small control error.

(3) The field test of harvesting rapeseed, millet and rice shows that: under the automatic height control system of the header, the error between the actual height of the crop when it is harvested and the set height is within 15 mm, the harvest effect is better, and the height of the crop stubble is relatively flat, satisfying the requirement of automatic control of the height of the combine harvester in the multi-crop growth environment. It also verifies the effect of the fuzzy PID control system designed in this paper in the actual test.

ACKNOWLEDGEMENT

I mainly completed the design of experiments and the writing of papers, Yaoming Li provided funding, and others provided trial assistance. Project source was the Major Science and Technology Innovation Project of Shandong Province: Key technology and Industrialization of intelligent and efficient crawler rape combined harvester (2019JZZY010729).

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