DESIGN AND TEST OF AUTOMATIC CONTROL SYSTEM FOR HEADER HEIGHT OF COMBINE HARVESTER
/
联合收获机割台高度自动控制系统的设计与试验

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ABSTRACT

Aiming at the problems of poor applicability of traditional header height detection mechanism, poor stability and large lag of automatic control system of combine harvesters, an automatic control system of header height of combine harvester was designed, which mainly included the profiling mechanism, controller, proportional valve, manual operation handle and display module. The profiling detection mechanism was composed of angle sensor, profiling plate, torsion spring and other structures. The key structural parameters of the profiling mechanism were determined by using the Adams simulation software and its working performance was verified. The gray prediction PID algorithm of header height was used to reduce the lag of the control model. The control system detected the height of the header from the ground through the profiling mechanism. After being processed by the controller, the height of the header was changed by adjusting the expansion of the header oil cylinder. The field test results showed that the working performance of the header automatic control system was stable. Under the working conditions of preset header height of 100 mm and 200 mm, the average deviation of the control system was within 21 mm, which met the real-time control demand of header height during the normal operation of the combine harvester. This research could provide intelligent design methods of combine harvesters.

摘要

针对传统联合收获机割台高度检测机构适用性差、自动调控系统稳定性不佳与滞后性大的问题，设计了一种联合收获机割台高度自动控制系统，主要包括随地仿形机构、控制器、比例阀、手动操作手柄和显示模块等。随地仿形检测机构由角度传感器、仿形板、扭簧等结构组成，利用 Adams 仿真软件确定了仿形机构关键结构参数并验证了其工作性能，建立了联合收获机割台高度与传感器信号之间的关系模型，采用割台高度灰色预测 PID 控制算法减小控制模型滞后性，控制系统通过仿形机构检测割台离地高度，经控制器处理后，通过调整割台油缸伸缩量实现割台高度变化。田间试验结果表明，割台自动调控系统工作性能稳定，在预设割台高度 100mm 及 200mm 工况下，控制系统调节的平均偏差均在 21mm 内，满足联合收获机正常作业时割台高度实时调控需求。本研究可为联合收获机的智能化设计提供参考。

INTRODUCTION

The combine harvester is one of the key links in job production. With the continuous maturity of joint harvest equipment, the direction of automation and intelligence has gradually become an important development direction (*Bomoi et al., 2022; Golpira et al., 2022; Kim et al., 2021; Mirmahdi et al., 2021*). The automatic control of the header height is an important aspect. As an important parameter in the operation process of the actual harvester (*Shukla et al., 2021; Shojaei et al., 2021*), the height of header is easy to cause ear loss and grain loss too high, and the increase of stubble height will significantly improve the operating power consumption of the cultivator and increase the operating cost. When the header height is low, it is easy to touch soil and cause machine failure (*Ni et al., 2021*).

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At present, the height control of the header of the combine mainly depends on the manual driving experience. The operation effect and efficiency vary from person to person, and the manipulator has strong manipulation intensity after working for a long time.

In order to reduce the strength of the driver, and improve the efficiency of the combine harvester, domestic and foreign scholars have carried out a large number of research on the height automatic control system of the combined harvesting machine header. *Yang et al., (2018*) arranged three pairs of ultrasonic sensors at the bottom of the cutting stage to achieve non-contact measurement of the ground height from the ground, the measurement effect is susceptible to the influence of the stubble and soil block. *Wei et al., (2017*) and *Geng et al., (2020*) designed contact mechanical feeler mechanism respectively. The mechanical change was converted into electrical signal output by angle sensor, thereby controlling the ground imitation action, but did not consider the latency of the system during the actual job. *Yang et al., (2022*) designed the ground profiling monitoring mechanism and the header height feedback mechanism based on the angle sensor, and the height error of cutting stubble was not more than 2 cm, which showed a stable control effect.

Aiming at the above problems, this paper designed a set of automatic control system for header height of combine harvester. The current height of the header was detected in real time by profiling mechanism and the mathematical model of the header height and angle sensor signal was established. The header height can be adjusted automatically by adjusting the stroke of the header cylinder. The field verification test was carried out, and the reliability of the height adaptive regulation system of the header was evaluated, which provided a reference for the intelligent design of the combine harvesters.

MATERIALS AND METHODS

Overall structure

The automatic header height control system provided the operator with manual and automatic operation modes. The manual operation handle was used to control the lifting of the header during manual operation. The manual operation handle was equipped with a manual and automatic mode switch. The manipulator can complete the switching of the working mode according to the actual needs. The automatic control system was mainly composed of profiling detection mechanism, header lifting cylinder, manual operating handle and other modules. The overall structure of header height automatic control system is shown in Figure 1.

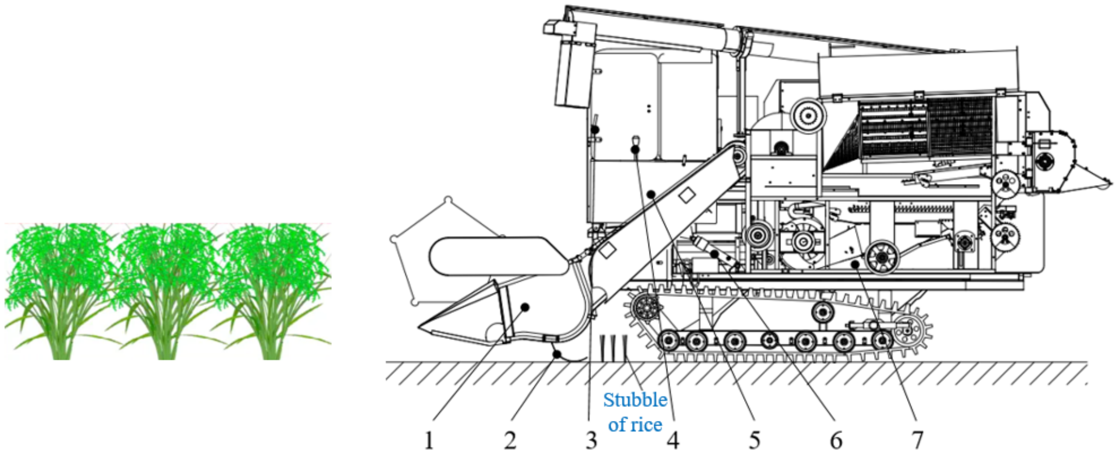


Fig.1 - The overall structure of automatic control system for header height

1. Header of combine harvester; 2. Profiling detecting mechanism; 3. Industrial display screen; 4. Manual operating handle; 5. Controller; 6. Header lifting cylinder; 6. Proportional valve

Working Principle

The profiling detecting mechanism was symmetrically installed on one side of the header, and the fluctuation of the ground was converted into voltage signal output through the angle sensor. The controller was a Bortron Selindro hydraulic controller specially designed for intelligent equipment of agricultural machinery, which was equipped with CAN bus interface communication function. The lifting of the header was controlled by a hydraulic system, and the hydraulic valve is a proportional solenoid valve, which can control the position of the hydraulic cylinder more accurately. The automatic header height control system detected the height of the header from the ground through the profiling mechanism. The controller output the control signal to the proportional valve according to the current header height. The proportional valve changed the hydraulic oil to push the header lifting cylinder to expand and contract, so as to adjust the header height to the set range. When the profiling mechanism detected that the current header height was greater than the upper limit of the set range, the controller output a signal to energize the electromagnet on the right side of the proportional valve, and the proportional valve spool moved to the right. The piston rod of the header cylinder shrank under the hydraulic oil pressure, and the header dropped; When the profiling mechanism detected that the current header height was less than the lower limit of the set range, the controller output a signal to energize the solenoid on the left side of the proportional valve, the proportional valve spool moved to the left. The header cylinder piston rod extended under the hydraulic oil pressure, and the header rose. The working principle of header height control is shown in Figure 2.

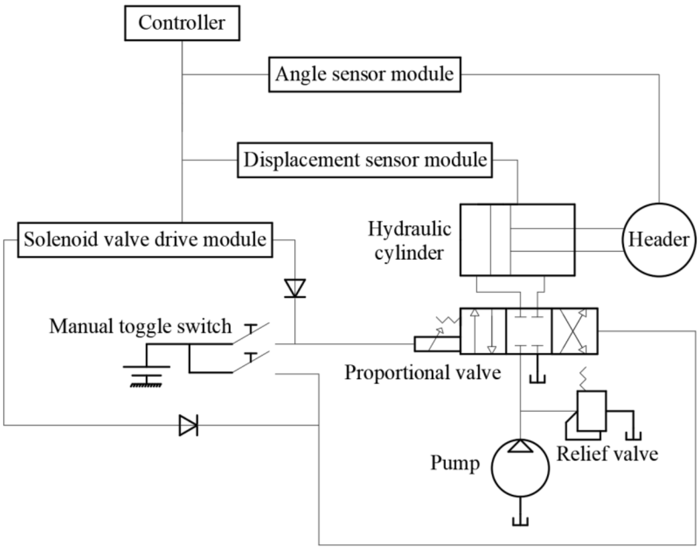


Fig. 2 - Working principle diagram of header height control

Profiling mechanism design

In order to measure the height of the combine header, a header height profiling mechanism was designed. In this section, the structure design of the profiling mechanism is carried out, and the structural parameters were optimized and its operation performance was verified through the multi-body dynamics simulation software Adams. The profiling detection mechanism for header height was mainly composed of profiling plate, torsion spring, angle sensor, mounting frame and other structures, as shown in Figure 3. The profiling plate was always in contact with the ground under the torsion spring pressure and its own gravity. The end of the profiling plate and the angle sensor were respectively fixed with the shaft through set screws. During operation, with the fluctuation of the ground, the profiling plate rotated around the axis, thus driving the sensing shaft of the angle sensor to rotate. Therefore, change of the header height can be obtained according to the angle sensor detection signal.

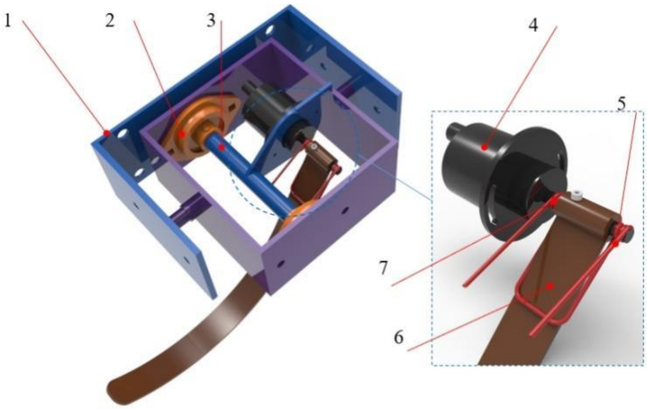


Fig.3 - Profiling mechanism structure diagram

1. The mounting frame; 2. Mounting flange; 3. Pin shaft; 4. Angle sensor; 5. Torsional spring; 6. Profiling plate; 7. Shaft

When the combine harvester is going backwards, a large contact force is produced with the soil by using straight profiling plate. Therefore, the grounding part of the profiling plate of the profiling mechanism was designed to be a combination of "straight line-arc curve". According to the actual operation experience of the operator, when the combine harvester is harvesting crops such as rice and wheat, the stubble height is generally controlled to be within the range of 50-300 mm *(Wang et al., 2015)*. Therefore, in order to ensure that the profiling mechanism can detect the header height within this range, the profiling plate was designed with a length of 110 mm for the straight part, a radius of 200 mm for the arc of the curved part, and an arc angle of 90°. Considering the influence of the structural strength of the profiling plate and debris such as field stones on the detection accuracy of the profiling mechanism, the width of the profiling plate was set to 32 mm and the thickness was set to 4 mm.

When the combine harvester reverses, the linear profiling plate will produce a large contact force with the soil, which will easily cause deformation or even destruction of the profiling mechanism. Therefore, the grounding part of the profiling plate of the profiling mechanism was designed as a combination of "straight arc curve". According to the actual operation experience of the operator, the height of stubble is generally controlled within 50-300 mm when harvesting rice, wheat and other crops with the combine harvester. Therefore, in order to ensure that the profiling mechanism can detect the header height within this range, the profiling plate was designed as a straight part with a length of 110 mm, a curved part with an arc radius of 200 mm and an arc angle of 90 °. Considering the influence of the structural strength of the profiling plate and sundries such as stones in the field on the detection accuracy of the profiling mechanism, the width of the profiling plate was set to 32 mm and the thickness was set to 4 mm.

LAT216 high-precision digital angle sensor was selected as the angle sensor in the profiling mechanism, with a range of 0-120 ° and a linear output of 0-5 V analog voltage signal to meet the requirements of the profiling mechanism designed to detect the stubble height.

ADAMS Simulation

The profiling mechanism designed should be able to detect the height of the header close to the undulating ground. The interaction between profiling plate and mounting frame, header and soil involves multi-body dynamics theory. In order to verify whether the profiling mechanism can meet the above functions, Adams multi-body dynamics simulation software was used to optimize the structural parameters of the profiling mechanism.

The multi-body dynamics model shown in Fig. 4 was established in the Adams software. In order to improve the efficiency of the simulation experiment, the profiling mechanism was simplified when establishing the simulation model *(Vahedi et al., 2021)*. The simplified model consisted of the header, mounting frame, profiled plate and ground. The ground model material was selected as soil, which set the density as $7.801\text{x}10^{-6}$kg/mm^3, the Young's modulus as $2.07\text{x}10^5$N/mm^2, the Poisson's ratio as 0.29, and the profiling mechanism material was set to ordinary carbon steel. After the model was established, the rotation pair was added to the mounting frame and profiling plate. A moving pair was added on the header and mounting frame, and a translational drive was added on the moving pair. The set drive speed was set to 1 m/s, and the profiling mechanism moved forward when simulating work. A spring flexible connection was added between the profiling plate and the mounting frame to analog the spring. The simulation model is shown in Figure 4. The simulation time was set to 5 s, and the step size was 0.01.

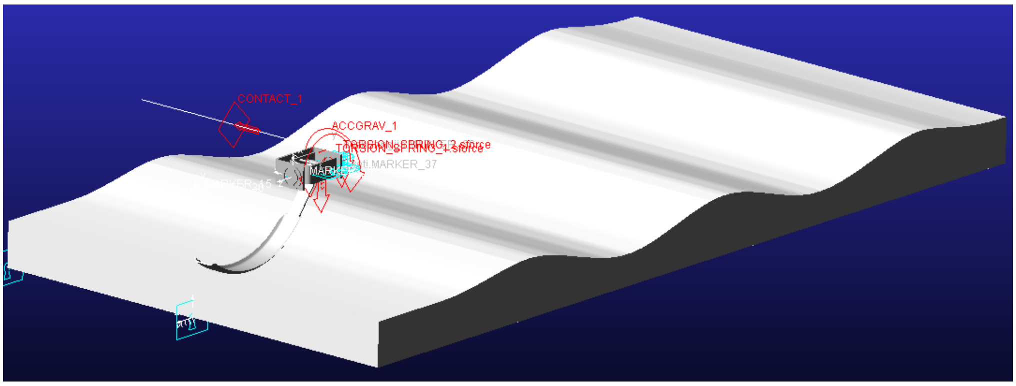
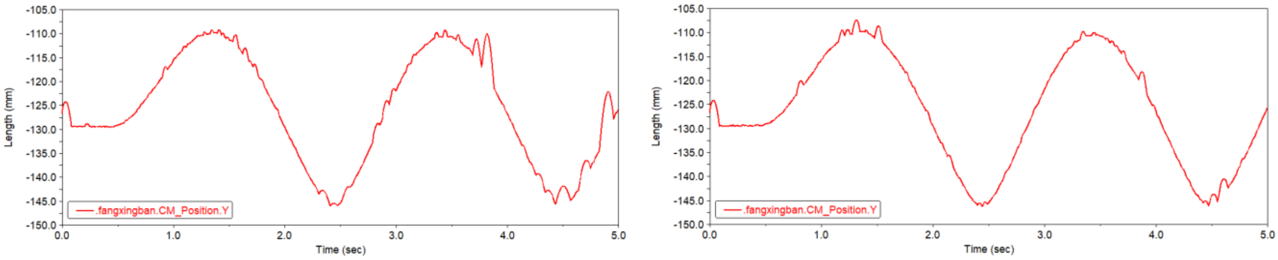
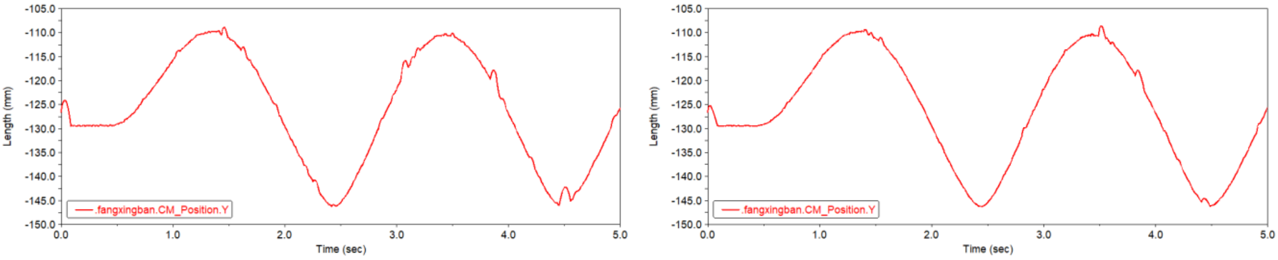


Fig. 4 - Adams simulation model of the profiling mechanism

In order to verify the ground copying ability of the profiling mechanism designed and determine the optimal torque of the torsion spring, the torsion spring torque was took as the influencing factor. We took four levels of torsion spring torque as 0 (no torque applied), 15 N·mm, 25 N·mm, 35 N·mm, and recorded the displacement curve of the Y-axis direction of the centroid point of the profiling plate. The corresponding displacement curve is shown in Figure 5.



(a) Torque M=0 N·mm (b) Torque M=15N·mm



(c) Torque M=25·N·mm (d) Torque M=35·N·mm

Fig. 5 - Displacement curves of Y-axis of centroid of profile plate under different torques

Analyzing the results shown in Figure 5, it is found that when the profiling plate was not affected by the torque of the torsion spring, there was a significant fluctuation in the displacement of the profiling plate's centroid in the Y-axis direction. With the increase of the torque of the torsion spring, the fluctuation decreased. When the torque is 35N·mm, the fluctuation decreased significantly. Considering that increasing the torque of the torsion spring will increase the resistance and cause the profiling mechanism to sink during wet field operation, the torque of the torsion spring is determined to be 35N·mm. Combined with the size parameters of the profiling mechanism, through the calculation formula (1) of the torsion spring, it was finally determined that the wire diameter of the torsion spring was 2 mm, the pitch diameter was 18 mm, and the effective number of turns was 6.

$$M = PR = \frac{Ed^4\alpha}{3660nD} \tag{1}$$

where: the P is load, N; R is the force arm length, mm; E is the elastic modulus, MPa; d is a line diameter, mm; α is the torsion angle, °; n is the number of effective turns of spring; D is the middle diameter of the spring, mm.

Automatic Regulation Strategy

The height regulatory system of the header needs to adjust distance between header and ground according to the ground undulation, and the choice of the highly regulated strategy of the header will directly affect the control performance of header. Because the height detection and profiling mechanism of the header designed in this paper is installed behind the cutter, the highly regulated process has the characteristics of nonlinearity and time lag, easy to be interfered by external factors. Traditional PID control effect is relatively poor. In order to improve control accuracy and stability, the header height is regulated using a gray prediction PID control algorithm, and the advantages of information-based gray prediction and easy-to-real PID control techniques were combined, and the parameters of the PID controller were adjusted online according to the prediction error and the change rate of the error output by the header height control system.

Calibration of profiling mechanism

This section first studied the relationship model between the header height of the combine harvester and the sensor signal. In order to establish the function relation between the output signal of the angle sensor of the profiling mechanism and the actual header height, the calibration test of the profiling mechanism was carried out. The header height was changed by manually adjusting the operating handle, and the height of the cutting knife from the ground was measured, that is the header height, with a tape measure, and the output voltage value of the angle sensor corresponding to different header height was recorded. Since the output of the angle sensor was linear, the relationship between the deflection angle of the copy plate and the output voltage is as follows:

$$U = k_1 \cdot \beta \tag{2}$$

where:

U is the output voltage of the angle sensor, V;
β is the rotation angle of the profiling plate, (°);
k_1 is the calibration factor of voltage and angle.

According to the test calibration, the relationship model between the header height and the rotation angle of the copy plate is as follows:

$$H = k_2 \cos\beta + c \tag{3}$$

where: H is the header height, m; k_2 is the calibration coefficient between the header height and the rotation angle of the profiling plate; c is a constant. From this, the functional relationship between the output voltage of the angle sensor and the header height is calculated, as in formula (4).

$$H = k_2 \cos\frac{U}{k_1} + c \tag{4}$$

Gray prediction PID controller

Usually, the gray model is represented by GM (M, N), where *M* represents the order of the model equation, and *N* represents the number of variables in the model equation (*Nurcan et al., 2021)*. The establishment of the grey prediction model of header height in this paper was based on the most widely used GM (1, 1) model. The sampling period is 0.5 s, the length is *n=4*, and the prediction step is *p=5*. Each sampling was brought into the formula (4) to obtain the height of the header $H^{(0)}(t)$, and the original sequence can be obtained as:

$$H^{(0)} = \{H^{(0)}(1), H^{(0)}(2), H^{(0)}(3), H^{(0)}(4)\} \tag{5}$$

The header heights were all positive, so the regularization was not required *(Cai Muzhen et al, 2021)*. The original sequence was accumulated, and then the accumulated generated sequence was obtained.

$$H^{(1)} = \{H^{(1)}(1), H^{(1)}(2), H^{(1)}(3), H^{(1)}(4)\} \tag{6}$$

Where:

$$H^{(1)}(k) = \sum_{m=1}^{k} H^{(0)}(m) \qquad (k = 1, 2, 3, 4)$$

Background values: $z^{(1)}(k)$:

$$\begin{cases} k = 2, z^{(1)}(2) = 0.5(H^{(1)}(1) + H^{(1)}(2)) \\ k = 3, z^{(1)}(3) = 0.5(H^{(1)}(2) + H^{(1)}(3)) \\ k = 4, z^{(1)}(4) = 0.5(H^{(1)}(3) + H^{(1)}(4)) \end{cases} \tag{7}$$

References get the development coefficient *a* and grey input *u (Asgari et al., 2021)*:

$$a = \frac{C \cdot D - E}{F - C^2} \tag{8}$$

$$u = \frac{F \cdot D - C \cdot E}{F - C^2} \tag{9}$$

Where:

$$\begin{cases} C = \sum_{k=2}^{4} z^{(1)}(k) \\ D = \sum_{k=2}^{4} H^{(0)}(k) \\ E = \sum_{k=2}^{4} z^{(1)}(k) \cdot H^{(0)}(k) \\ F = \sum_{k=2}^{4} (z^{(1)}(k))^2 \end{cases} \tag{10}$$

After the above parameters are obtained, the predicted value of the header height after p steps is obtained $\hat{H}{}^{(0)}(4+p)$:

$$\hat{H}{}^{(0)}(4+p) = \left[H^{(0)}(4) - \frac{u}{a} \right] e^{-ap}(1-e^{-a}) \tag{11}$$

The header height automatic control system detected the height of the header from the ground through the profiling mechanism. After the gray prediction, the control deviation e (t) was obtained by comparing the height with the given height. The PID control algorithm was used to calculate the system output. The control system drives the electromagnetic reversing valve through the solenoid valve drive module to control the expansion and contraction of the header hydraulic cylinder, thus realizing the automatic control of the header height. The control principle was shown in Figure 6.

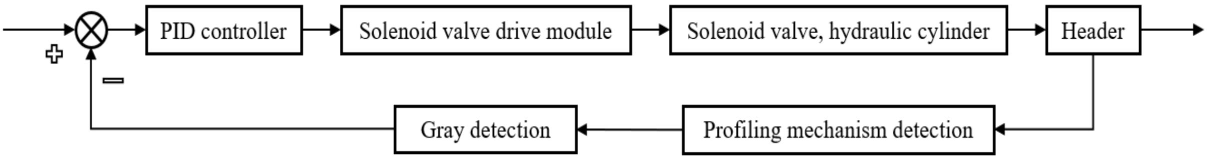


Fig. 6 - Schematic diagram of gray prediction PID control of header height

Matlab Simulink analysis

In order to further verify the proposed header height control strategy, optimize the working parameters of the header height automatic control system, and observe the dynamic response of the system in real time, a simulation model was built in the Matlab Simulink module, which is shown in Figure 7.

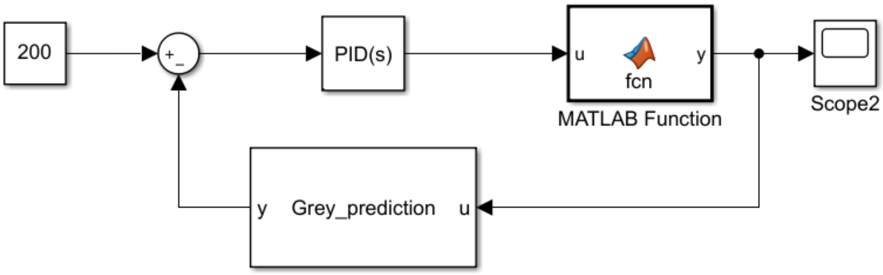


Fig.7 Simulation model of header height regulation in Matlab

In the simulation process, the setting time was 5 s, and the sampling time was 0.01 s. After calculation optimization, when the proportional coefficient K_p=1.57, the integral coefficient K_i=0.78, the differential coefficient K_d=0.8, and the input was 200 mm, the maximum output value of the PID controller was 210.6 mm, the steady state value was 194.7 mm, and the overshoot was 5.3%, the stabilization time was 0.9 s, the response speed was fast, and the overshoot is small, which can meet the design requirements of the automatic control system for the header height, The step response curve is shown in Figure 8. It can be seen that the control effect of the gray prediction PID control technology was significantly better than that of the PID control technology, the response time was relatively short, and the overshoot was relatively small, thus improving the control stability of the header height and obtaining a good control effect.

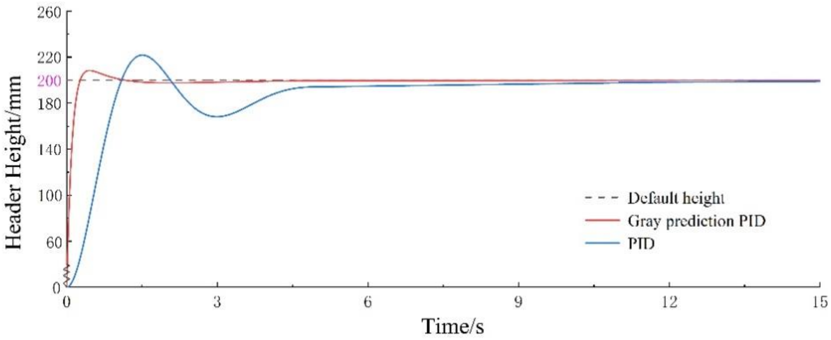


Fig. 8 - Step response curve of gray prediction PID control

Control system programming

The input signal of the automatic control system of the header height included 2 analog signals (2 profiling mechanisms), and the output signal consisted of 2 electromagnetic reversing valves and 1 electromagnetic relief valve. The flow chart of the automatic control system for the header height is shown in Figure 9.

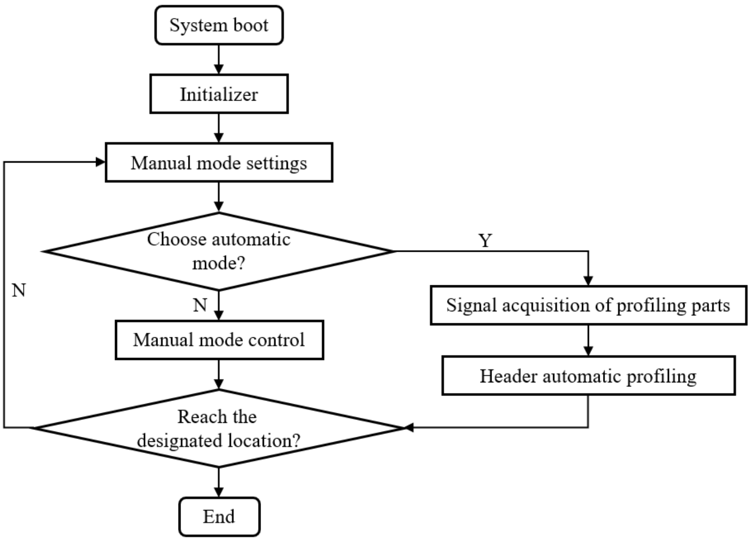


Fig. 9 - The header height control flow chart

When the system startup, the operator initialized the header height in manual mode and set the ideal header height range. In the automatic mode, the profiling mechanism performed signal monitoring, and after eliminating the wrong data, the current header height was obtained according to the functional relationship between the detection data of the profiling mechanism and the header height, and the predicted value of the header height was obtained according to the gray prediction model of the header height.

Compared with the given value, after analysis and processing by the controller, the on-off of the solenoid valve was controlled after the operation and amplification of the solenoid valve drive module, so as to realize the automatic regulation of the header height. When the header height was higher than the upper limit of the set range, the oil cylinder of the header was drive to lower position to reduce the header height. When the header height was lower than the limit of the set range, the oil cylinder of the header was driven to increase the header height.

RESULTS

On November 10, 2021, the field test of automatic control of the header height was carried out at Dafeng farm, Yancheng City, Jiangsu Province. The experimental rice varieties were Jiangfeng NO.1. The properties measured before harvesting were shown in Table 1. The test site is shown in Figure 10.

Table 1

Properties of experimental wheat crops

Project	Natural height	1000-grain weight	Grass to valley ratio	Production
/	[cm]	[g]	/	[kg/hm^2]
Value	76	39	1.28	8000

Fig.10 - Field experiment site of combine harvester

During the experiment, after the combine harvester entered a stable operation state, the manual/automatic control switch of the header height to the automatic state was pushed, and the header height was regulated by the automatic control system. The display terminal collected and saved the header height information in real time.

In the test, two sets of header heights were set 100 mm and 200 mm, respectively, and the harvesting was 10 meters under the automatic control mode of the header height. During the harvesting process, the software recorded the header height in real time. After harvesting, each sampling position was set every 0.5 meters along the forward direction of the harvester, and 5 sampling points were set along the vertical direction of the harvester through each sampling position. With a total of 100 sampling points, the height of the stubble after harvesting, representing the actual height of the header was measured.

The actual measured header height was compared with the set header height to evaluate the automatic control system of header height. The test data are shown in Fig.11.

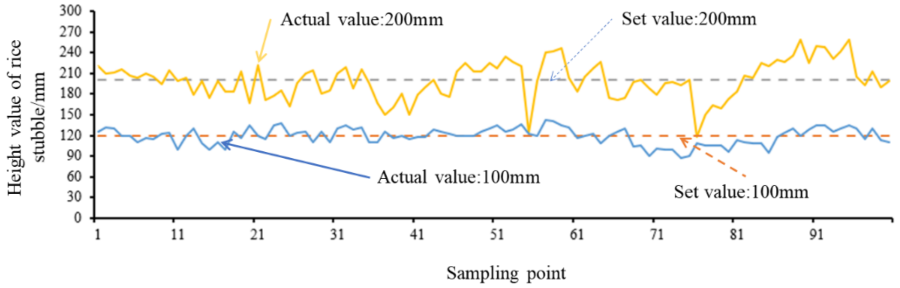


Fig. 11 - The actual stubble height when the height of the header was set to 100 mm or 200 mm

The test results show that when the header height was set to 100 mm, the average height of the actual stubble was 104.6 mm, the average deviation was 14.7 mm, and the maximum deviation was 31 mm. When the header height was set to 200 mm, the average actual stubble height was 192 mm, the average deviation was 20.6 mm, and the maximum deviation was 43 mm. The test results showed that the designed automatic control system for the header height has strong reliability under different setting of the header height. In general, the average deviation between the actual header height and the set header height can be controlled within 21 mm, which met the needs of field work.

CONCLUSIONS

1) Aiming at the problem that the header height of the domestic combine harvester mainly depends on manual operation by manual experience, a set of adaptive control system for the header height of the combine harvester was designed in this study, which provides users with two modes of manual operation mode and automatic control mode. The research on the height control of the harvester header provides a reference.

2) In order to detect the header height, a profiling mechanism was designed, and the parameters of the torsion spring were optimized by Adams simulation. At the same time, the simulation proves that the designed profiling mechanism can detect the header height closely to the undulating ground.

3) In order to realize the automatic control of the header height, the geometric relationship of the combine harvester header was analyzed, and the header height control model based on the grey prediction algorithm was established. The field test results show that the error between the actual header height and the set header height is within 21 mm, which meets the field operation requirements of the combine harvesters.

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