Development of the automatic navigation system for combine harvester based on GNSS

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Abstract: An automatic navigation system was developed to realize automatic driving for combine harvester, including the mechanical design, control method and software design. First of all, for the harvester modified with the automatic navigation system, a dynamic calibration method of the rear wheel center position was proposed. The control part included the navigation controller and the steering controller. A variable universe fuzzy controller was designed to the navigation controller, which used fuzzy control to change the fuzzy universe of input and output dynamically, that means, under the condition that the fuzzy rules remain unchanged, the fuzzy universe changes with the change of input, which is an adaptive fuzzy control method and can modify the control strategy in time. To realize the automatic navigation of the harvester, the decision result of the navigation controller based on the variable universe fuzzy control was input into the steering controller, and then the electric steering wheel was controlled to rotate. To test the performance of the designed automatic navigation system, the field experiment was carried out. When the combine harvester was navigating linearly at a speed of 0.8 m/s, the overall root mean square error (RMSE) of the lateral deviation was 5.87 cm. The test results showed that the system was designed could make the combine track the preset path smoothly and stably, and the tracking accuracy was at the centimeter level.

Keywords: automatic navigation system, combine harvester, GNSS, development, dynamic calibration, variable universe adaptive fuzzy control

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1 Introduction

The automatic navigation of agricultural machinery is an important supporting technology for achieving accurate agricultural machinery operation and a key technology for implementing precision agriculture[1-4]. Automatic navigation systems can effectively reduce the areas of repetitive and missing work and improve work efficiency and quality.

Ding and Wang[5] designed a combine harvester visual navigation control system to detect the harvested and unharvested boundary lines using a histogram-based navigation path fusion algorithm. Ding et al.[6] proposed an estimation algorithm for the double-tangential large curvature path turning radius based on the linear detection of the rotating projection for the difficult detection of combine harvesters' large curvature path. Wu et al.[7] proposed a straight line detection algorithm for the walking target of the grain combine harvester based on improved Hough transform for the visual navigation of grain combine harvesters. Wei et al.[8] developed an on-line recognition system for combine harvesters using laser nondestructive testing technology. The automatic driving system of a combine harvester can automatically track driving according to the harvest boundary. The automatic navigation system of the combine harvester can automatically perform track driving according to the harvest boundary. Guo[9] carried out the design and research of an automatic navigation control system for sugarcane harvesters. Xu and Zhou[10] used the principal component analysis (PCA) algorithm to extract features, performed PCA of the segmented images, and rotated the image spindle into the horizontal direction to match the training sample library. Finally, the navigation roadmap was recognized, and the preset path was automatically generated.

Anon et al.[11] designed an electro-hydraulic circuit and installed it in the traditional hydraulic steering circuit of a small agricultural tractor. They used PID controller to adjust the hydraulic valve, and then realized the speed and position control of the steering. Chin-Tan et al. used a wheeled mobile robot as a test platform, by optimizing the design of PID controller parameters in the path tracking task, effectively reducing the process of manually adjusting parameters, so that the DC motor of the controller could be better driven[12]. Gao et al.[13] independently developed a mechanical detection angle sensor for detecting crop rows and returning the detection value as a deviation to the guidance controller. The experimental results at three different speeds showed that the average error was below 0.1 m, which met the

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navigation requirements of the maize combine. Nam et al.[14] designed a PI tracking controller, which directly controlled the steering wheel through the motor and performs feedback compensation. The control system had good stability and robustness. Takai et al.[15] designed a crawler tractor capable of autonomous navigation, using a hydrostatic system for steering and shifting, and the horizontal mean square error of the linear navigation test was less than 0.05 m. Backman et al.[16] used a nonlinear model predictive control method to control the steering of the tractor through a hydraulic system, and the lateral deviation was less than 0.1 m at a speed of 3.33 m/s, which realized the tractor's precise tracking of the straight path.

There are many uncertain factors when navigating in the field, thus, many researchers use fuzzy control to simplify complex problems and describe the entire time-varying control process through fuzzy language. To improve the stability of the automatic navigation rice transplanter path tracking system, Tang et al.[17] proposed a path tracking method that used fuzzy control to adjust the forward-looking distance of the pure tracking model. Ding et al.[18] designed a GPS-combined fuzzy control farmland robot navigation system, and established fuzzy control rules and database according to the navigation angle and navigation distance to determine the walking route of the farmland robot between rows. Guo and Chen[19] studied field autonomous mobile weeding robots based on machine vision navigation, using fuzzy control methods to guide the weeding robots to walk automatically along crop rows. Zhang et al.[20] constructed a fuzzy control method for the autonomous navigation rice seeding machine, which improved the navigation accuracy and dynamic performance. Zhang[21] designed a fuzzy control strategy to realize the automatic navigation control of agricultural tractors, which enables the system to track the preset path quickly and accurately. To produce an efficient and effective path planning for mobile robots, Abdalla et al.[22] proposed a method based on the combination of a modified APF algorithm with fuzzy logic. Rath et al.[23] proposed a fuzzy logic controller hybridized with generic algorithm for path planning of a humanoid robot to avoid obstacles present in a cluttered environment and reach the target location successfully. Ma et al.[24] proposed an autonomous navigation algorithm using visual cues and fuzzy control for Wolfberry orchards.

In general, research on the automatic navigation system of wheat combine harvesters is mainly based on machine vision navigation, which is affected by weather, light, and other factors. Moreover, steering control is mostly achieved by modifying the hydraulic valve group oil circuit. Electronically controlled hydraulic steering has the advantages of high control accuracy and fast response. However, its system transformation is difficult, and it is not easy to promote in practical applications. The electric steering wheel has the advantages of convenient installation, strong applicability, and has the function of manual automatic switching, which meets the functional requirements of the end-effector in this study.

In terms of path tracking methods, many scholars have conducted a lot of research, mainly including the modern control methods using optimal control theory, the forward-looking distance tracking models for selecting preview points, the PID control methods based on the idea of error feedback, and intelligent control methods such as fuzzy control. The optimal control strategy can get a good control effect in the linear region, however, the effect is not good in the control of the nonlinear agricultural machinery model. The preview point control algorithm simulates human driving behavior, which is robust and predictable, however the adaptive determination of the forward-looking distance is difficult to achieve. The PID control algorithm is simple, highly reliable, and convenient to adjust, however it is difficult to set the parameters. It requires a certain amount of experience and a lot of parameter simulation and setting tests. The sliding mode structure control method requires certain measures to reduce chattering. Fuzzy control does not need a precise agricultural machinery model, but the fuzzy division of input and output is fixed. As the error in the walking control process becomes smaller, the fuzzy controller adjustment becomes rough and the adaptability becomes worse. In response to these problems, this study provides a new idea, try to combine different control methods, complement each other to get better control effects.

First, according to the mechanical structure design of the navigation system, this study proposed a dynamic calibration method for the rear wheel center position for the harvester after the automatic navigation system was modified. Then, the variable universe method was introduced into the design of the harvester navigation fuzzy controller, and the basic universe of input and output variables was adjusted in real-time by the expansion factor of the universe, which improved the dynamic characteristics and stability accuracy of system control, and increased the adaptive ability of the system. The decision result of the navigation controller based on the variable universe fuzzy control was input into the steering controller based on the PID algorithm, and then the electric steering wheel was controlled to rotate, so as to realize the efficient autonomous navigation operation of the harvester according to the predetermined path on the complex ground. Finally, the above control algorithm was tested in the wheat field.

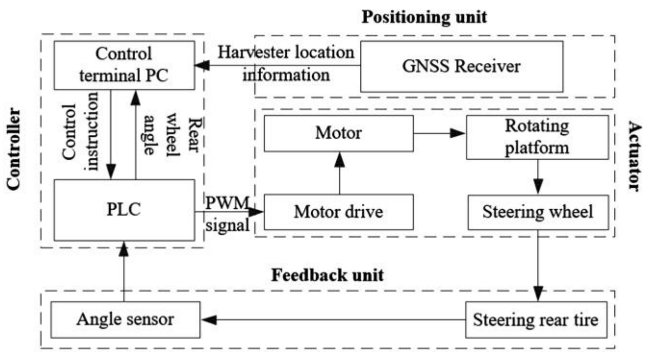
2 Materials and methods

2.1 Overall design of the system

Figure 1 shows that the combine harvester automatic navigation system, which includes four parts, namely, a positioning unit, a controller, an actuator, and a feedback unit. Among these parts, the Global Navigation Satellite System (GNSS) receiver (i.e., the positioning unit) is used to obtain the position information of the combine harvester in real-time. The controller part combines the industrial computer and the Programmable Logic Controller (PLC), and they are interrelated and coordinated and inseparable, the former provides sufficient computing power for the navigation control algorithm, and the latter provides reliable control for real-time signal transmission. In the actuator part, the high-precision stepping motor with a small step angle drives the hollow shaft rotating platform, which is stable and fastened with the steering wheel, realizes the high-precision and high-torque control of the steering wheel, and determines the steering control of the combine harvester. The feedback unit detects the rear-wheel angle as the vehicle steering angle provides feedback to the PLC and then transmits it to the upper machine and forms an external closed-loop control[25].

2.1.1 Construction of a combine harvester navigation system platform

A Xinjiang-2A wheat combine harvester was selected for equipment installation according to the technical requirements of the navigation system. Figure 2 shows the industrial computer, GNSS positioning antenna and receiver (N71J-AU, Huace Navigation Technology Inc., China), mechanical steering structure, integrated PLC control box, and rear-wheel angle detection device installed on the combine harvester. The positioning accuracy of the N71J-AU GNSS receiver is at the centimeter level, its horizontal static positioning accuracy is 1 cm, and its vertical static positioning accuracy is 1.5 cm. To ensure the positioning effect of the agricultural automatic navigation system, the GNSS receiver with a parameter adjustment and a horizontal antenna calibration can obtain high dynamic positioning accuracy with a standard deviation of less than 5 cm in the case of differential positioning[26]. The system mainly obtained the positioning information through the GNSS, and the industrial computer was used as the vehicle control terminal for information collection and decision calculation of the control quantity, which was transmitted to the PLC. The PLC outputted pulse and direction signals to the stepping motor, which controlled the steering wheel rotation and received the detection information of the rear–wheel angle to feedback to the industrial computer. Thus, the influence of various nonlinear factors in the system was effectively corrected and compensated by the terminal controller, increasing the precision of control.



Note: PLC represents Programmable Logic Controller; PWM is the abbreviation of pulse width modulation, the same as below.

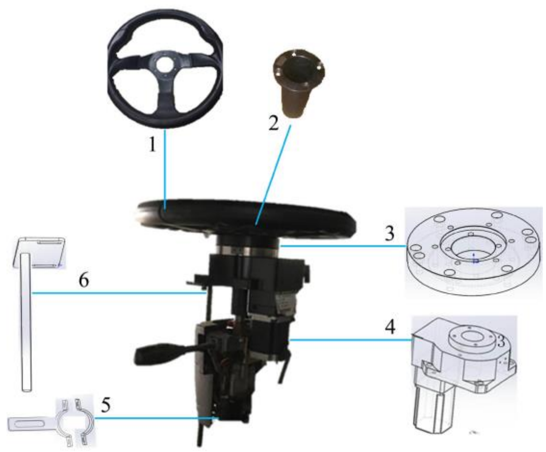
Figure 1 Overall design of the automatic navigation system of combine harvester

Figure 2 Physical diagram of system platform

2.1.2 Mechanical design of the combine harvester navigation system

1) Steering control device of combine harvester

In terms of automatic steering technology, steering wheel control does not need to change the steering mechanism of the combine harvester. It can replace the traditional hydraulic valve group, and it is also suitable for non-hydraulic steering mechanisms. The steering wheel adopting motor-driven has little change to the steering system, and the installation is simple. The mechanical design of the automatic steering mechanism is shown in Figure 3. The steering wheel control device is mainly composed of a stepping motor, a hollow rotary table, a transmission power ring, a spline slot, a steering wheel, a clamp bracket, and a support rod. The spline slot and the steering wheel are separated for easy installation. The spline slot and the transmission power ring are fixed by screws, and the transmission power ring is mounted on the top end of the motor rotating platform assembly. This combination was uniformly placed on the spline on top of the steering shaft to ensure that the steering shaft spline was engaged with the spline slot, thereby keeping the hollow shaft rotating platform concentric with the steering shaft. During the automatic navigation process, the rotation of the hollow shaft rotating platform should drive the transmission power ring and the spline slot to rotate synchronously using the motor power-on, thereby driving the steering shaft to rotate and control the steering of the combine harvester. Therefore, the hollow shaft rotating platform must be fixed externally; the bottom end of the rotating platform was fixed by the screw hole and the bracket on the support rod, and the support rod was fixed on the steering shaft shell using a clamp bracket. Finally, the steering wheel was mounted on the upper surface of the transmission power ring to facilitate switching to manual driving in emergency situations or turning at the edge of a field. The device was assembled from various structural parts, therefore, the failure target can be locked and repaired in time, and it was also a type of low-cost equipment.



1. Steering wheel 2. Spline slot 3. Transmission power ring 4. Combination of motor rotating platform 5. Clamp bracket 6. Support rod

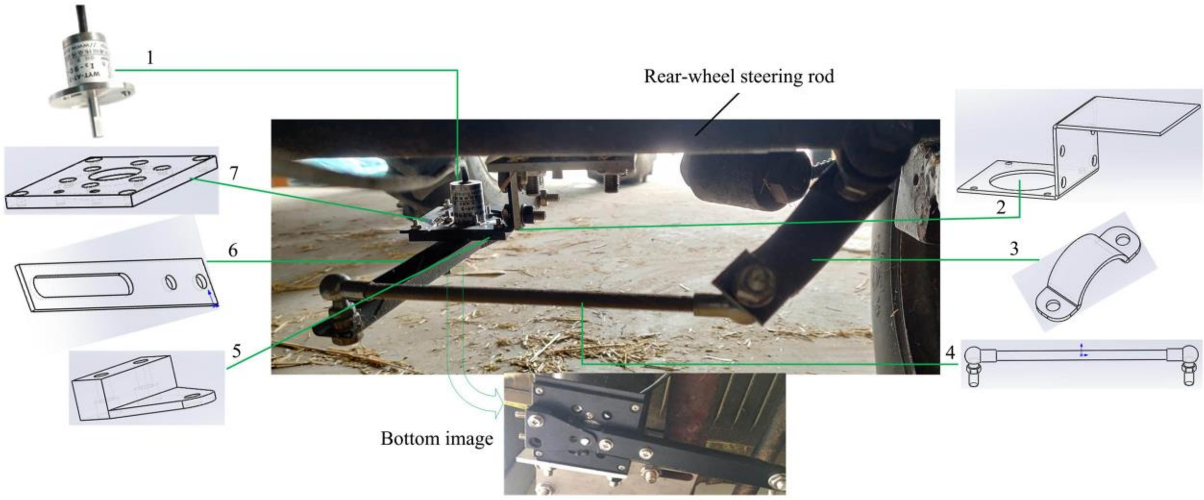
Figure 3 Steering control device mechanical structure

The steering torque of the combine harvester was less than 10 N·m, the torque of the stepping motor was 2 N·m, and the torque of 20 N·m could be the output after the rotating platform reached a reduction ratio of 1:10. The rotating platform transmission was a single-stage-deceleration mode of worm drive. When the stepper motor driver was set to 800 pulses/r, the ratio of the turning angle of the rear wheel to the output pulse was 1:454, and the speed range of the stepping motor was 150-1200 r/min. When the control frequency was 1 Hz, 0.2 s was subtracted from the acceleration time set for the motor. In theory, the stepper motor can drive the wheel to 28°/s, which can fully satisfy the automatic navigation requirements of the combine harvester.

2) Detection device of steering angle of combine harvester

Figure 4 shows that the rear-wheel steering angle detecting device is mainly composed of an angle sensor, an angle sensor bracket, a connecting clamp, a ball head connecting rod, an angle sensor reinforcement block, a swing arm, and an angle sensor base. Given that the combine harvester is driven by the front wheel and turned by the rear wheel, the steering direction of the vehicle body is opposite to that of the rear wheel. When the steering wheel is in the same direction as the vehicle body, the steering angle measured by the angle sensor at this time is defined as the vehicle's median angle, that is, the steering wheel deflection angle is 0°. The angle sensor bracket, the angle sensor base, and the reinforcement block are used to mount the steering angle detecting device upside down under the rear axle of the combine harvester, that is, the measured rear-wheel steering angle is turned to the left to be positive and to the right to be negative. Thus, the steering angle of the entire combine harvester body is turned to the left to be negative and to the right to be positive. The consistency of the detection angle and the direction of rotation of the steering wheel is ensured, which is convenient for the subsequent design of fuzzy control rules. During the steering of the vehicle, the swing arm must be aligned with the tire direction to ensure that the ball head connecting rod is parallel to the steering rod in front of the rear axle of the combine harvester. During the steering of the vehicle, the steering rod drives the connecting clamp fastened thereto to move laterally. The swing arm is swung left and right by the ball head connecting rod, thereby driving the axis of the angle sensor to rotate and detect the steering angle of the combine harvester. Through the ball head connecting rod, the displacement of the steering rod in different planes can be converted into the swing angle of the angle sensor. This method can subtly solve the problem of damage to the sensor due to the difference between the angle sensor and the rear wheel steering shaft of the combine harvester.

The angle sensor adopts the WYT-AT-3 type from Beijing Tongciweiye Company that can output a 4-20 mA detection current and whose detection angle range and resolution are 0°-360° and less than or equal to 0.05°, respectively, which can meet the steering angle measurement of the combine harvester.



1.Angle sensor 2. Angle sensor bracket 3. Connecting clamp 4. Connecting rod 5. Reinforcement block of angle sensor 6. Swing arm 7. Angle sensor base

Figure 4 Mechanical structure of the detection module of steering angle

2.1.3 Dynamic calibration method of the rear wheel middle position of the combine harvester

The steering angle feedback control is the relative amount when the rear wheel is in the middle position. Since the initial position of the angle sensor cannot be kept consistent at each time, the initial current value of the middle position must be calibrated. According to the mechanical structure design of the navigation system, a dynamic calibration method was proposed for the rear wheel center position of the harvester after the automatic navigation system was modified. The specific steps are as follows:

Step 1: Install the angle sensor, when the rear wheel is near the middle position, adjust the angle sensor so that its output is about 12 mA (range is 4-20 mA).

Step 2: Start the combine harvester and drives along with a fixed straight line at a certain speed, and the driving time is at least 60 s;

Step 3: After starting and running for about 10 s, it is basically stable, collect the 40 s middle position current at a sampling frequency of 10 Hz.

Step 4: Calculate the average value and mean square error of 400 middle position currents. When the mean square error is lower than 0.05 mA, it is judged that the calibration is valid, otherwise it will be repeated. Through such calibration, an accurate median current can be obtained, and the dynamic error is less than 0.25°, which meets the accuracy requirements.

The calibration result is of great significance to the automatic steering system. Firstly, the accuracy of the middle position current directly determines the polarity of the control quantity, which is the directionality of the steering. Secondly, the middle position current of the rear wheel obtained by driving in a straight line shields the manufacturing process of the vehicle's steering rear wheel itself and improves the accuracy of the automatic steering system.

2.2 Control method of the system

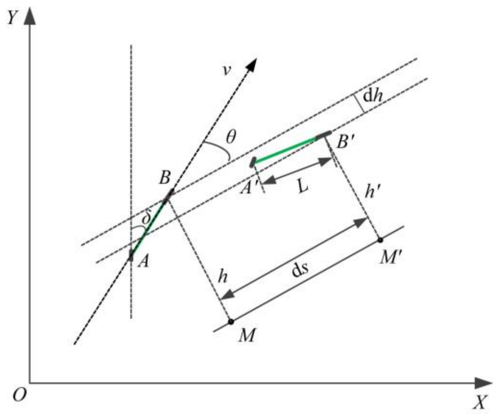
2.2.1 Linear path kinematics modeling of combine harvester

Establishing an accurate vehicle kinematics model is the research basis for improving the accuracy of the navigation control in agricultural machinery navigation[27]. Instead of a two-wheeler model of the front-wheel steering vehicle, such as a tractor, the combine harvester was based on a two-wheeler model of the rear-wheel steering. A pure geometry method was used to describe the movement of the combine harvester mathematically, and the transverse kinematics model of the combine harvester was established. The following assumptions were made: the ground is flat, the forward speed is constant, and the vehicle centrifugal force and side slip are ignored. According to the structure and motion characteristics of the wheat combine harvester, the harvester was simplified into a kinematics analysis on the basis of the front axle center of the two-wheeler model, and the antenna was directly above the center of the driving axle. A simplified kinematic model is shown in Figure 5, where point M is the point closest to control point B on the preset straight path.

On the basis of the above kinematic model diagram and combined with geometric knowledge and physical laws, the differential equations[28] of the kinematic model when the path traced by the combine harvester is a straight line can be expressed as follows:

$$\begin{cases} \dfrac{\mathrm{d}s}{\mathrm{d}t} = v\cos\theta \\ \dfrac{\mathrm{d}h}{\mathrm{d}t} = v\sin\theta \\ \dfrac{\mathrm{d}\theta}{\mathrm{d}t} = \dfrac{v\tan\theta}{L} \end{cases} \tag{1}$$

where, X and Y are the coordinate systems in which the combine harvester is located; θ is the heading deviation angle of the combine harvester, (°); δ is the rear-wheel deflection angle of the combine harvester, (°) (equal to the steering angle of the vehicle body, and measured by angle sensor); v is the combine harvester's speed, m/s; L is the wheelbase of the combine harvester, m; s is the length of point M along line MM' with an initial value of 0, m; h is the relative preset of the lateral deviation of the combine harvester of linear path MM', m.



Note: A and B are the rear wheel and front wheel of the harvester respectively; θ is the heading deviation angle of the combine harvester, (°); δ is the rear-wheel deflection angle of the combine harvester, (°) (equal to the steering angle of the vehicle body, and measured by angle sensor); v is the combine harvester's speed, m/s; L is the wheelbase of the combine harvester, m; s is the length of point M along line MM' with an initial value of 0, m; h is the relative preset of the lateral deviation of the combine harvester of linear path MM', m, the same as below.

Figure 5 Diagram of the kinematics model of combine harvester

By modeling the specific system and adjusting the parameters of the specific control model adaptively, the control delay of the control system can be effectively reduced. The navigation and steering control principle diagram is shown in Figure 6. The control unit mainly includes a navigation controller and a steering controller. According to the current position and heading information obtained by GNSS, and the established kinematic model, the lateral deviation h and heading deviation angle θ of the combine harvester relative to the target navigation line can be calculated. Taking h and θ as the input parameters of the navigation decision controller, using variable universe adaptive fuzzy control algorithm, by introducing input and output universe expansion factors β and γ, the fuzzy universe can be adjusted in real time to obtain high-precision expected steering angle $r(t)$. Based on the difference between $r(t)$ and the current rear wheel steering angle δ, the output steering angle $e(t)$ is obtained, and be used as the input of the steering controller. Finally, the pulse signal $u(t)$ obtained by the PID steering controller is input into the actuator to realize the lateral control of the harvester and make it automatically navigate according to the preset path.

2.2.2 Design of navigation controller based on adaptive fuzzy control algorithm with variable universe

The following conditions must be satisfied to achieve automatic driving. First, the agricultural machinery needs a special positioning device to determine the real-time position of the agricultural machine. Second, a suitable control algorithm for navigation control must be designed. Considering the high nonlinearity of the wheat combine harvester navigation system and the complex and variable work environment, the fuzzy control algorithm for path tracking was designed[16-18,29]. Although it does not rely on accurate mathematical models, fuzzy control requires expert experience to formulate fuzzy control rules. Fuzzy control has strong subjectivity and is prone to static errors. Therefore, the vehicle state information contained in the vehicle model established in this study should be fully excavated to improve the performance of the navigation system.

The performance of the fuzzy controller is proportional to the number of control rules. In conventional fuzzy control, adding control rules will cause problems such as "rule explosion", and too many rules will make the controller very complicated and not conducive to implementation. In the control process, as the system error gradually decreases to near 0, the original fuzzy division becomes rough, making the fuzzy controller unable to play its due role. The variable universe fuzzy control method is to introduce the universe contraction-expansion factor to make the universe of input and output variables shrink and expand correspondingly with the decrease or increase of the error under the condition that the control rules remain unchanged, which is equivalent to increasing the control rules and improving robustness and adaptive ability of fuzzy control.

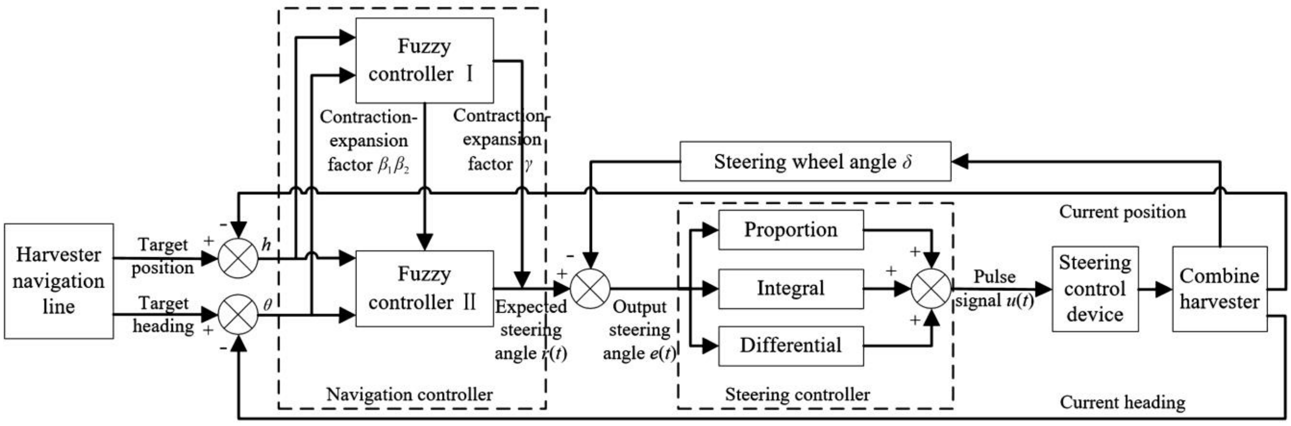


Figure 6 Navigation and steering control principle diagram

As shown in the navigation controller part in Figure 6, the variable universe adaptive fuzzy control is carried out in two steps:

Step 1: Fuzzy controller I adjusts the universe according to the lateral deviation h and heading deviation θ obtained by the system model, and then obtains the input and output universe expansion factors β_1, β_2 and γ of fuzzy controller II after inference;

Step 2: Use the expansion factor to change the fuzzy division of the fuzzy controller II to obtain the structure of the new fuzzy controller II, and then use the new fuzzy controller to reason about the expected steering angle $r(t)$ of the harvester.

Among them, the basic universes of input variable lateral deviation h and heading deviation θ are $X_1=[-E_h, E_h]$, $X_2 = [-E_\theta, E_\theta]$. The basic universe of the output variable expected steering angle $r(t)$ is $Y=[-U, U]$. $A=\{A_i\}$, $B=\{B_i\}$, and $C=\{C_i\}$, $(1\leq i\leq m)$ are the fuzzy divisions on the universes X_1, X_2, and Y respectively. A, B, C are language variables. And h_i, θ_i, $r_i(t)$ denote the peak points of A_i, B_i, and C_i respectively. Then there are fuzzy inference rules: If h is A_i and θ is B_i, then $r(t)$ is C_i.

The variable universe fuzzy control can be combined with both the quantization factor and the scale factor in practical application, which is easy to understand and realize. The so-called variable universe means that X_1, X_2, and Y can be adjusted automatically with the changes of h, θ. The expansion factors of the universe of input and output variables are respectively denoted as $\beta_1(h)$, $\beta_2(\theta)$, and $\gamma(r(t))$, then the basic universe becomes

$$X_1(h) = [-\beta_1(h)E_h, \beta_1(h)E_h] \quad (2)$$

$$X_2(\theta) = [-\beta_2(\theta)E_\theta, \beta_2(\theta)E_\theta] \quad (3)$$

$$Y(r(t)) = [-\gamma(r(t))U, \gamma(r(t))U] \quad (4)$$

It can be seen from the above equations that the universe adjustment can be realized by multiplying the corresponding expansion factor. In the control process, the fuzzy set universe of fuzzy controller II shrinks as the input becomes smaller, or expands as the input becomes larger. The expansion of the universe can increase the value of fuzzy control language variables and control rules, thereby improving the control accuracy.

1) Design of fuzzy controller I

The choice of universe expansion factor has a great influence on the performance of the fuzzy controller, and it needs to satisfy duality, zero-preserving, monotonicity, synergy, and regularity. Fuzzy controller I in Figure 6 is a fuzzy controller with an expansion factor of universe. Its definition is as follows:

$$x_1(t) = |h|/E_h \quad (5)$$

Choose $x_1(t)$ and $\beta_1(t)$ as the input and output variables of the fuzzy controller I, and the fuzzy subset is defined as {zero (O), small (S), medium (M), large (L)}. The fuzzy universe of the input variable $x_1(t)$ is [0, 1]. The membership function of each fuzzy subset is Gaussian function, and the fuzzy reasoning rules are shown in Table 1.

Table 1 Fuzzy control rule of universe contraction-expansion factor

Variable	Fuzzy inference rules			
$x_1(t)$	O	S	M	L
$\beta_1(h)$	O	S	M	L

Note: $x_1(t)$ and $\beta_1(h)$ are the input and output variables of fuzzy controller I respectively. O: Zero; S: Small; M: Medium; L: Large.

From the fuzzy controller I, the expansion factors $\beta_1(t)$ and $\beta_2(t)$ of the input universe X_1 and X_2 can be inferred respectively. Since the purpose of the navigation controller is to make, $\lim_{t\to\infty}h=0$ and $\lim_{t\to\infty}\theta=0$, that is $\lim_{t\to\infty}\beta_1=0$ and $\lim_{t\to\infty}\beta_2=0$. Therefore, $\gamma(t)$ and $\beta_1(t)$, $\beta_2(t)$ can be regarded as a linear relationship, and then it can be defined as:

$$\gamma(r(t))=\alpha\beta_1(h) +(1-\alpha)\,\beta_2(\theta),\ \alpha\in(0,1) \quad (6)$$

where, α is the correction factor. By adjusting the value of correction factor α to change the weighting degree of $\beta_1(h)$ and $\beta_2(\theta)$, to adjust the expansion factor of the output universe: When the lateral deviation h is large, the weight of $\beta_1(h)$ should be increased to improve the system response speed to rapidly eliminate the lateral position deviation. When the lateral deviation h is small, the weight of $\beta_2(\theta)$ should be increased to reduce the system overshoot to improve the system stability.

(2) Design of fuzzy controller II

The input variables of the fuzzy controller II are h and θ, and the output is $r(t)$. The input and output universe undergoes the change of the contraction-expansion factor, so that the structure of the fuzzy controller changes accordingly. The key to designing fuzzy controller II lies in the design of the initial universe fuzzy controller. The fuzzy rule base is the core part of fuzzy control. The rule base of fuzzy control enables the system to simulate the control decisions of people.

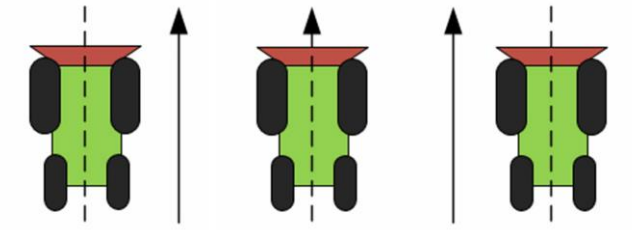
Before designing the control rules, the signs of lateral deviation, heading deviation, and body steering angle are as follows. When the navigation vehicle is at the right side of the navigation line, the lateral deviation is positive and the left side is negative, the heading deviation is positive clockwise and negative anticlockwise, and the steering angle of the vehicle body turns to the right to be positive and to the left to be negative. Notably, the measured rear-wheel steering angle is turned to the left to be positive and to the right to be negative. Hence, the steering angle of the entire combine harvester body is turned to the left to be negative and to the right to be positive. The kinematics model of the two-wheeled vehicle linear path established in this research can be used to analyze the movement state of the combine harvester. When the deviation is large, the control amount reduces the deviation as much as possible; when the deviation is small, the stability of the system must be considered in addition to eliminating the deviation.

The positional relationship between the vehicle and the predefined path was divided into nine states, as shown in Figure 7. According to the driver's strategy for controlling the vehicle, a corresponding steering control strategy was established. Control intensity refers to the magnitude of deflection of the steering wheel. Set the initial universe of the fuzzy controller for the lateral deviation h, the heading deviation θ and the expected steering angle $r(t)$ as [−30 cm, 30 cm], [−15°, 15°] and [−12°, 12°], respectively[26]. According to the degree of variable fuzzy, it can be divided into seven fuzzy subsets, namely, negative large (NL), negative medium (NM), negative small (NS), zero (O), positive small (PS), positive medium (PM) and positive large (PL). Based on 7 fuzzy subsets of 2 input parameters, 49 fuzzy rules can be obtained as shown in Table 2, all of which use triangular functions as membership functions.

Table 2 Fuzzy rules reasoning for expected steering angle

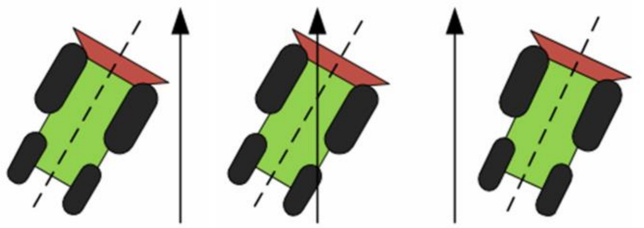
Lateral deviation	Heading deviation(θ)						
(h)	NL	NM	NS	O	PS	PM	PL
NL	PL	PL	PM	PM	PS	PS	O
NM	PL	PM	PM	PM	PS	O	NS
NS	PM	PM	PS	PS	O	NS	NM
O	PM	PM	PS	O	NS	NM	NM
PS	PM	PS	O	NS	NS	NM	NM
PM	PS	O	NS	NM	NM	NM	NL
PL	O	NS	NS	NM	NM	NL	NL

Note: NL: Egative large; NM: Negative medium; NS: Negative small; O: Zero; PS: Positive small; PM: Positive medium; PL: Positive large.



a. θ is zero, and h is negative b. θ is zero, and h is zero c. θ is zero, and h is positive

d. θ and h are negative e. θ is negative, and h is zero f. θ is negative, and h is positive



g. θ is positive, and h is negative h. θ is positive, and h is zero i. θ and h are positive

Figure 7 Position relationship between combine harvester and preset path

2.2.3 Design of steering controller based on PID

A PID method was used for the steering controller, which combines the proportional, integral, and derivative of the output steering angle of the fuzzy controller to form the control quantity of the motor through a linear combination to control the controlled object (steering wheel). PID is often used for controlled objects with large inertia and large hysteresis characteristics. Due to the large size of the whole machine, the harvester had the problem of large inertia and hysteresis. Therefore, PID was used to adjust its steering. Its control law is shown in Equation (7).

$$u(t)=K_p\left(e(t)+\frac{1}{T_I}\int_0^t e(t)\mathrm{d}t+T_D\frac{\mathrm{d}e(t)}{\mathrm{d}t}\right) \tag{7}$$

where, $u(t)$ is the motor steering wheel angle pulse control amount at time t; $e(t)$ is steering wheel steering angle deviation at time t; K_P is the proportion factor; T_I is the integral coefficient; T_D is the differential time constant.

The input of the PID steering controller is the deviation $e(t)$ between the expected steering wheel angle and the current steering wheel angle, and its output is the target steering angle pulse control amount of the electric steering wheel. This part can be regarded as a combination of ratio and a section of inertia, and the transfer function is shown in Equation (8).

$$\frac{u(s)}{\delta(s)}=\frac{k_n}{t_n s+1} \tag{8}$$

where, u is the target turning angle of the steering wheel; δ is the steering angle of the rear wheel of the harvester; k_n is the gain of the harvester steering system; t_n is the time constant of the harvester steering system.

2.3 Design of system software

According to the field operation requirements of the navigation system of the combine harvester, in-vehicle terminal software suitable for the automatic navigation of the combine harvester was developed. The control accuracy, security, and stability of the navigation system depend on the rational development of the vehicle terminal software.

As shown in Figure 8, the software function modules are the data sending and acquisition, processing, storage, and display parts. The interface display includes a display of real-time pose, job path, and navigation status of the combine harvester, as shown in Figure 9.

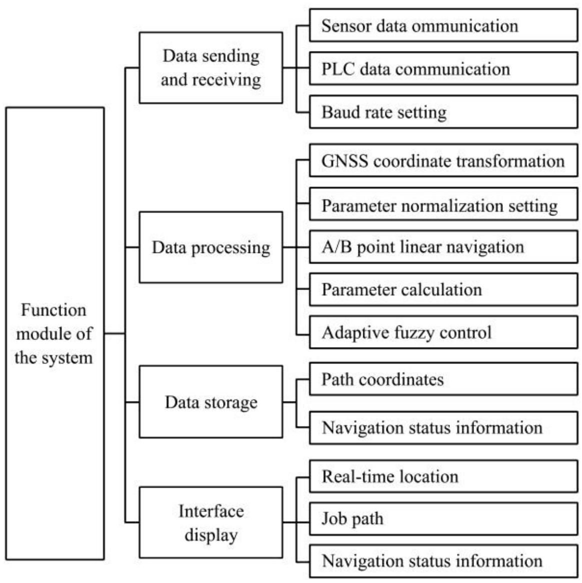
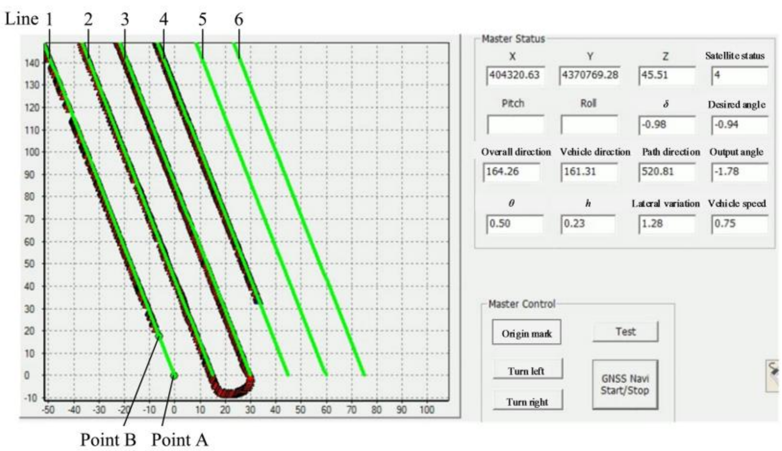


Figure 8 Vehicle terminal software function module diagram



Note: The red lines are the automatic driving trajectory of the harvester, and the green lines are the preset route navigation line.

Figure 9 Vehicle terminal software interface

The navigation system used an industrial computer as the vehicle terminal processor. The system adopted Windows 7. The development language utilized C++/MFC. Finally, the development environment was the convenient and efficient Visual Studio 2010.

3 Results

To verify the reliability and rationality of the developed automatic navigation system of the combine harvester, a linear navigation test was designed in the wheat field, as shown in Figure 10. The automatic driving speed of the combine harvester was 0.8 m/s, and the communication frequency is 5 Hz. The experiment was conducted at the China Agricultural University of Zhuozhou Experimental Station on June 21, 2021.

As shown in Figure 9, when the combine was harvesting in the wheat field, straight-line navigation automatic driving experiments were carried out six times. The navigation deviation information on the fourth route is shown in Figure 11. The results of the six groups of experiments are summarized in Table 3. Through calculation, the error of the average absolute value is 3.820 cm, and the overall root mean square error of the lateral deviation absolute value is 5.870 cm. Take a certain navigation line to perform Matlab trajectory fitting, and the navigation effect is shown in Figure 12.

Figure 10 Field test of combine harvester navigation system

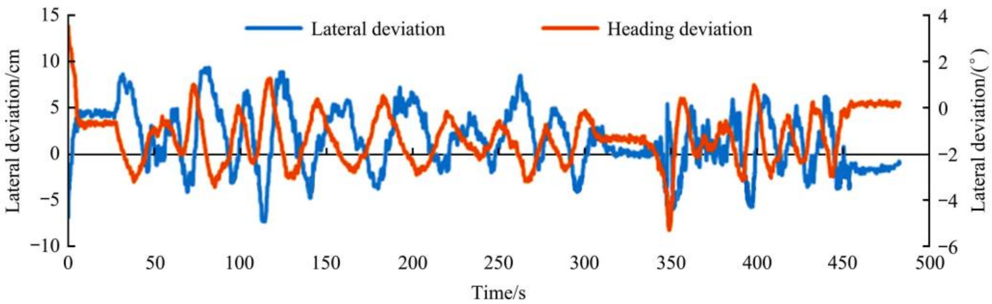


Figure 11 Diagram of deviation information

Table 3 Results of the navigation experiments in the wheat field

Line number	Time /s	Maximum error/cm	Minimum error/cm	Average absolute error/cm	Root mean square error/cm
1	134.2	7.59	0	2.238	2.942
2	120.4	19.45	0	4.635	6.529
3	209.6	16.18	0.01	5.072	6.568
4	482.8	9.37	0	2.836	3.546
5	108.2	11.81	0.01	5.118	5.939
6	222.0	8.29	0.01	2.994	3.619
Overall	/	/	/	**3.820**	**5.870**

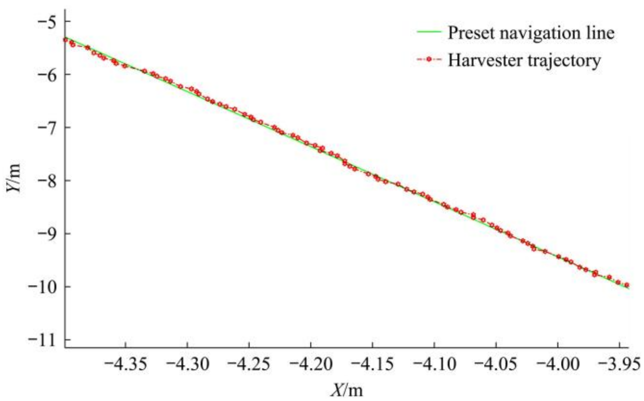


Figure 12 Navigation effect of the harvester's trajectory

4 Conclusions

1) The automatic navigation system of wheat combine harvesters was developed. In accordance with the characteristics of the combine's steering mechanism, the corresponding steering mechanism and steering angle detection structure were designed, and a dynamic calibration method for the rear wheel middle position was proposed.

2) A navigation controller based on variable universe adaptive fuzzy control method and a steering controller based on PID algorithm were designed. Using the universe contraction-expansion factor to adjust the basic domain of input and output variables in real-time can make the accuracy and dynamics of fuzzy control better. This study provides a new idea, try to combine different control methods, complement each other to get better control effect.

3) In the wheat harvesting scene, from the straight-line multi-group automatic tracking test, it could be seen that the overall average and total root mean square value of the horizontal deviation of the automatic driving of the combine harvester were 3.82 cm and 5.87 cm, respectively. The results show that the automatic navigation system of the harvester developed in this study can accurately realize the combine harvester to track the preset path smoothly and stably, and the tracking accuracy is at the centimeter level.

In addition, because the combine harvester needs to carry out wheat harvesting operations, the vehicle body has a large vibration phenomenon. To reduce the errors in the automatic navigation operation of the combine harvester, subsequently, new control strategies will continue to be explored. For example, research work such as attitude and positioning data fusion and adaptive Kalman filtering will be carried out to eliminate the influence of vibration and noise from GNSS positioning and orientation data during the wheat harvesting operation.

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