DESIGN AND EXPERIMENT OF SPRAY BOOM INCLINATION CONTROL SYSTEM / 喷杆倾角控制系统的设计与实验

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ABSTRACT

During field operations of the spray boom sprayer, the distance between the ends of the spray boom and the height of the crop canopy affects the uniformity of spraying, requiring operators to manually adjust the spray boom to be parallel to the crop canopy, which impacts operational efficiency. This study presents the design of a boom tilt control system, consisting of a main control node, distance measurement node, vehicle tilt detection node, and spray boom tilt control node. The bus communication protocol for the spray boom tilt control system is defined according to the ISO11783 standard, and a serial communication network is designed, along with the development of a real-time dynamic monitoring interface for the spray boom. The system automatically monitors the height of the boom and the tilt of the vehicle, makes decisions based on the detection information, controls the electric actuator, and adjusts the tilt of the boom. Leveraging the advantages of fast computing speed and user-friendly human-machine interface of the PC, as well as the high cost-effectiveness and small size of the microcontroller, and the multi-master-slave structure of the CAN bus, this system can complete data acquisition, processing, and other functions required for spray boom tilt control, achieving automatic adjustment of spray boom tilt. This enhances spray uniformity and operational efficiency of the sprayer, while reducing the workload of operators.

摘要

喷杆喷雾机田间作业时，喷杆两端距离作物冠层的高度影响喷雾均匀性，需要操作人员手动将喷杆调整到与作物冠层平行，影响作业效率。本文设计了一种喷杆倾角控制系统，包括主控节点、测距节点、车体倾角检测节点和喷杆倾角控制节点。根据 ISO11783 协议定义了喷杆倾角控制系统总线通信协议，进行了串行通信网设计，开发了喷杆实时动态监控界面。本系统能自动监视喷杆高度和车体倾角，并根据检测信息做出决策，控制电动推杆，调节喷杆倾角。本系统充分发挥了 PC 机运算速度快和人机交互界面友好、单片机性价比高且体积小、CAN 总线多主从结构等优点，能够完成喷杆倾角控制所需数据的采集、处理等功能，实现喷杆倾角自动调节，从而提高喷雾均匀性和喷雾机作业效率，减轻操作人员的劳动强度。

INTRODUCTION

As of 2020, the mechanized control of various crops in China accounted for 48.5% of the total control area. The area of mechanized and intelligent plant protection operations continues to expand, with wide-width boom sprayers being widely used (*He et al., 2022*). Spray quality is one of the important factors affecting the effectiveness of pesticides, and spray uniformity is an important indicator of spray quality (*Qi et al., 1999*). The height of the nozzle relative to the target significantly affects the uniformity and drift of the spray. During field operations of boom sprayers, the harmful vertical and rolling rigid movements of the boom are the main causes of uneven spray distribution. Simulation results have shown that boom rolling can cause a spray deposition of up to 10 times the standard dose (*Roman et al., 1997*). Reducing the amplitude of vertical oscillation of the boom can reduce the coefficient of variation of the spray, thereby improving spray uniformity (*Chen et al., 2008*).

Due to the long boom of wide-width boom sprayers and the small size of the vehicle, even slight movements can cause significant displacement at the end of the boom (*Qiao et al., 2017*).

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Especially when the ground excitation frequency is close to the natural frequency of the boom, the oscillation of the boom intensifies, severely affecting spray quality and even causing damage to the end of the boom touching the ground (*Cui et al., 2019*). The boom moves parallel to the ground under the influence of gravity and vertically within the plane perpendicular to the ground under the effect of ground excitation. When the sprayer is operating on sloping terrain, the height of the boom ends from the crop canopy varies, thus affecting spray uniformity. Operators need to manually adjust the boom to a parallel position with the crop canopy or the ground, which not only affects spray uniformity but also hampers operational efficiency and increases labour intensity for operators (*Li et al., 2023*).

Some research has been conducted on the control system of the spray boom. Three contact sensors are used to detect the distance between the spray boom and the ground, and a hydraulic cylinder is used to extend or retract and control the elevation or lowering of the spray boom (*Wang Songlin, 2014*). In order to keep the spray boom parallel to the crop canopy or the ground, ultrasonic sensors placed at both ends of the spray boom are used to detect the position of the spray boom. The position of the spray boom is adjusted by controlling the hydraulic cylinder using Siemens S7-200PLC and a single-chip microcomputer to achieve online adjustment of the spray boom (*Anthonis et al., 2005; Chen et al., 2013; Cui et al., 2017, 2019; Wei et al., 2015*). Multiple sensors, including laser radar, are used to measure the distance between the spray boom and the crop canopy, and a microcomputer and PLC are jointly used to control the adjustment of the spray boom height (*Wang et al., 2023*). To adjust the position of the spray boom during the operation of the sprayer, a spray boom levelling mechanism is constructed using balance cylinders, springs, and air dampers to adjust the position of the spray boom (*Wang et al., 2016*).

Therefore, this paper focuses on the design of an active suspension system for wide-width spray boom sprayers. A control system based on fieldbus technology is adopted. Ultrasonic distance sensors located at both ends of the spray boom are used to collect the height of the spray boom from the crop canopy or the ground. Tilt sensors are used to detect the attitude of the spray boom. The collected data, after removing abnormal values, is uploaded to the host computer via the fieldbus. The host computer integrates the attitude and height information of the spray boom, analyses the status of the spray boom, and controls the drive device according to the system requirements to adjust the attitude of the spray boom, thereby maintaining the height of the spray boom from the crop canopy or the ground. This improves spray uniformity, reduces the workload of operators, and enhances the efficiency of spray operations.

MATERIALS AND METHODS

THE STRUCTURE OF THE SPRAY BOOM ANGLE CONTROL SYSTEM

The overall structure of this system is shown in Figure 1. In the figure, Node 1 is responsible for measuring the vehicle body inclination angle, Node 2 and Node 3 are responsible for measuring the distance between the spray boom and the crop canopy or ground, and Node 4 is responsible for driving the electric actuator. These four nodes are installed on the spray boom and the vehicle body, so 51 series microcontrollers are used due to their high cost-effectiveness, high integration level, and strong anti-interference capabilities. The PC node is mainly responsible for analysing the data transmitted from each node and issuing commands to the control devices in each node based on the analysis results. Therefore, the entire spray boom angle control system consists of a PC, four microcontrollers, and communication lines. Due to the requirement for real-time performance in this system, a high-performance PC is selected to fully leverage the advantages of fast processor calculation speed and large storage capacity. This enables the PC to quickly perceive the various parameters in the control system and respond rapidly to on-site equipment. In addition to the PC node, the other nodes are based on the STC12C5A60S2 microcontroller, which integrates functions such as data acquisition, processing, communication, and control. These nodes are responsible for collecting the vehicle body inclination angle, measuring the height between the spray boom and the crop canopy, and controlling the angle of the spray boom.

SYSTEM HARDWARE DESIGN

Sensor selection, installation, and interface circuit design

Ultrasonic sensors have the advantages of having a constant propagation speed and direction in the same medium as the vibration direction, strong directionality, small size, fast data processing speed, high accuracy, easy installation and maintenance, and the ability to achieve non-contact measurement (*Alexandre et al., 2011*).

They are also not affected by external light, electromagnetic waves, weather, or the colour of the measured object itself, and have a certain degree of adaptability to harsh environments such as dust and smoke (*Liu, 2006*). The range of the spray boom distance from the crop canopy or ground is 10-1500 cm, and the walking speed is relatively fast, so it is required that the ranging sensor has a fast response speed and good real-time performance. In addition, the field operation environment is complex, so this paper selects the KS109 integrated ultrasonic ranging sensor produced by Guiding Technology Co., Ltd., as shown in Figure 2 (a), which has a detection range of 0.04-10 m and meets the system design requirements. The ultrasonic sensor is installed at both ends of the spray boom to measure the distance between the two ends of the spray boom and the crop canopy or ground, as shown in Figure 2 (b).

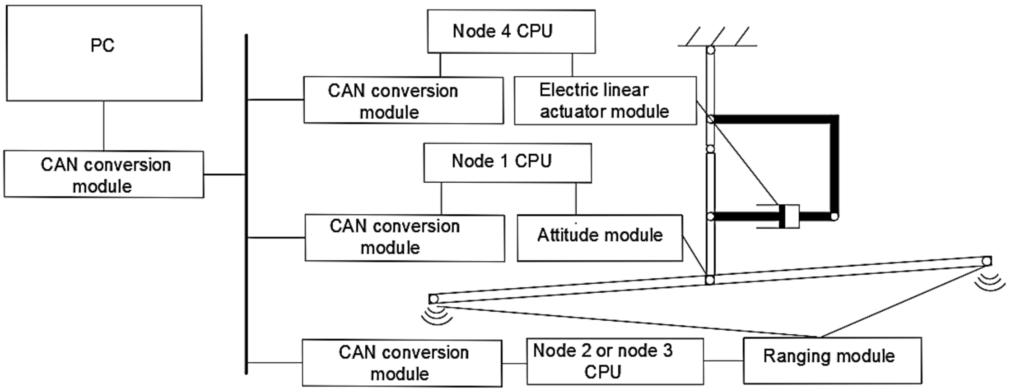
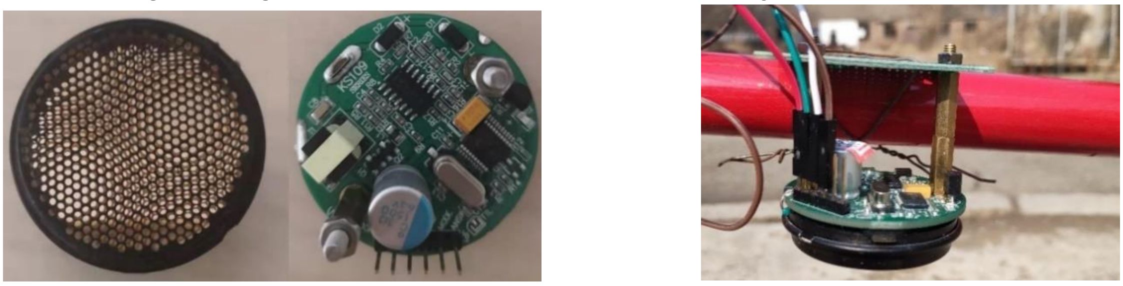


Fig. 1 - The general structure of the inclination control system of the boom



(a) Physical Picture of KS109 (b) Installation Position of KS109

Fig. 2 - KS109 ultrasonic sensor

The rotation angle of the sprayer vehicle body is an important indicator of the spray boom angle control system. This system needs to detect the swing angle of the vehicle body, and its selection also determines the performance of the spray boom angle control system. Considering the factors of speed and angular velocity sensitivity, the MPU6050 is chosen as the tilt measurement chip for this system (*Gu, 2019; He, 2020*). The WT901 uses the MPU6050 as the angle measurement chip, with a static accuracy of 0.05° and dynamic accuracy of 0.1°, which meets the system design requirements. Since the tilt sensor measures the swing angle of the vehicle body, the tilt sensor is installed on the frame as shown in Figure 3.

Fig. 3 - Installation position of inclination sensor

The sensor interface circuit is shown in Figure 4, which includes the interface circuits for ultrasonic ranging sensors and angle sensors. The tilt angle sensor WT901 communicates with the microcontroller through a serial port. The serial output terminal TX of WT901 is connected to the serial input terminal RXD of the microcontroller, and the serial input terminal RX of WT901 is connected to the serial output terminal TXD of the microcontroller. WT901 and the microcontroller share the same power supply. The KS109 uses an I2C interface to communicate with the microcontroller, sharing the power supply with the microcontroller.

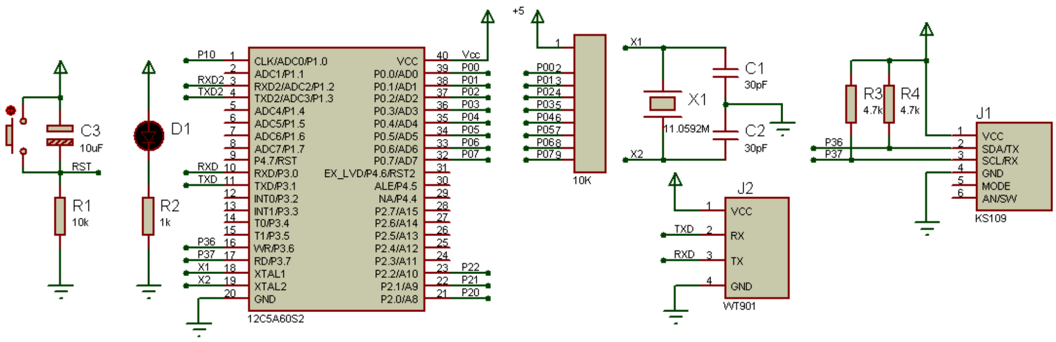
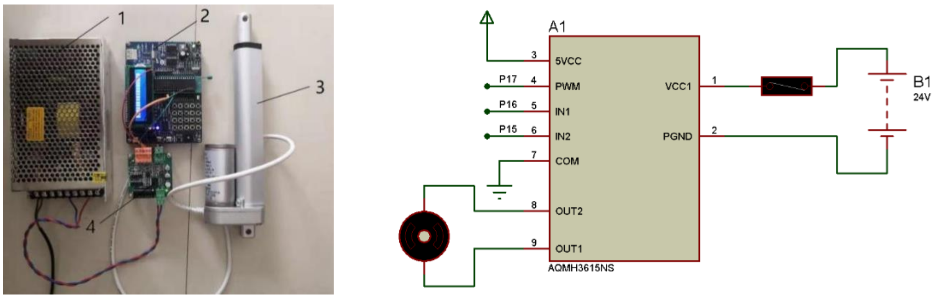


Fig. 4 - Interface circuit between the sensors and SCM

Selection and design of the drive device interface circuit

The electric actuator has advantages such as small size and high precision. It converts the rotational motion of the motor into linear motion of the actuator. It mainly consists of a motor, actuator, control device, and other mechanisms. It can be controlled by a power supply, reducing the need for pneumatic devices and reducing the overall weight of the device. Driving the electric push rod is actually driving the motor, and the I/O port of the microcontroller cannot directly drive the motor. Therefore, the AQMH3615NS driver is selected to drive the electric push rod, as shown in Figure 5(a).



(a) Drive device (b) Interface circuit

Fig. 5 - Motor drive device and interface circuit

1. Power supply; 2. Microcontroller system board; 3. Electric actuator; 4. AQMH3615NS

The driving power supply for the electric actuator is 24 V, while the power supply for the microcontroller is 5 V. The working power supply of the motor is separated from the power supply of the microcontroller system to prevent the motor's surge current from causing the microcontroller control system to malfunction. The motor driver interface circuit is shown in Figure 5(b). The microcontroller's P1.5 and P1.6 pins are used to control the direction of the motor, and the microcontroller's P1.7 pin outputs PWM (Pulse Width Modulation) to control the DC motor's speed, thereby controlling the operating speed of the electric actuator.

Serial communication hardware circuit design

Taking into account factors such as communication transmission distance, transmission speed, bus utilization, network characteristics, transmission mode, and fault tolerance mechanisms, this system adopts a CAN bus interface. Therefore, the input and output signals of each node during communication are all CAN interface signals. The system uses CAN transceiver modules to achieve the conversion between TTL signals and CAN interface signals, as shown in Figure 6(a). To improve the reliability of the system, the bus connections between nodes are made using CAN bus connectors, as shown in Figure 6(b). Shielded cables are used for the transmission lines between nodes, with a termination resistor of 120Ω installed at the designated positions as shown in Figure 6(c).

(a)CAN conversion module (b)CAN bus connector (c)Terminal resistor

Fig. 6 - CAN bus

SOFTWARE DESIGN OF SPRAY BOOM ANGLE CONTROL SYSTEM

Distance measurement and algorithm design

Due to the influence of temperature changes on ultrasonic distance measurement, the microcontroller measures the temperature every half an hour in order to compensate for the detected values of the ultrasonic sensor. When the ultrasonic sensor detects distance, the microcontroller uses analog I2C communication to measure the distance. Since the values collected by the ultrasonic sensor are calibrated at a temperature of 25℃, and temperature has a significant impact on the speed of sound propagation, the microcontroller converts the distance detected at 25℃ to the actual distance using equation (1).

$$V = 346.675+0.607T \tag{1}$$

where:

T is the difference between the current temperature and 25°C,
V is the speed of sound propagation at the current temperature.

Since the CAN bus sends data in packets of 8 bytes, and each distance measurement takes up two bytes, the microcontroller continues to collect distance information after each measurement. After collecting distance data four times, it sends a frame of data to the CAN bus. The specific flowchart is shown in Figure 7.

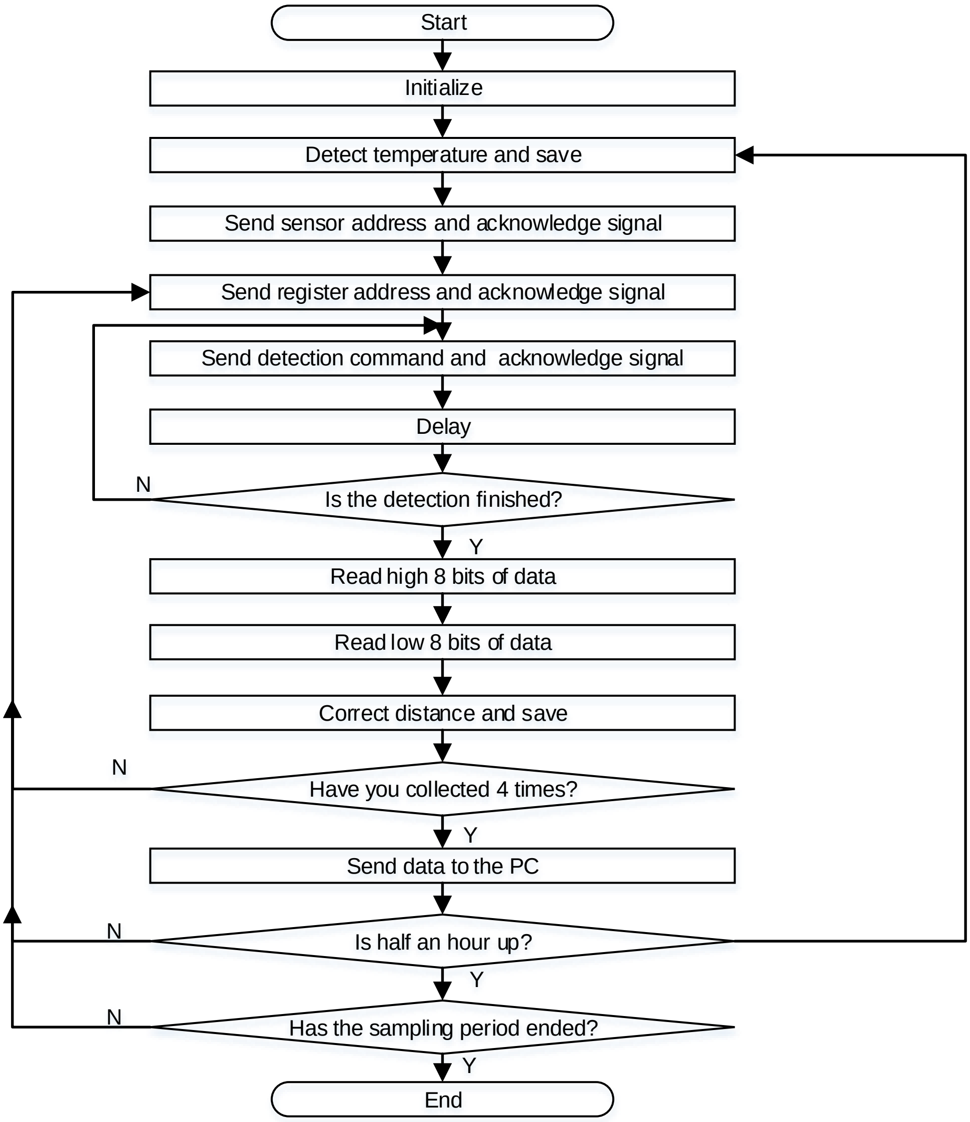


Fig. 7 - Flow diagram of distance measurement

In response to the occurrence of pests and diseases in maize crops at different growth stages, pesticide application operations are carried out. If the current monitoring is the distance between the spray rod and the crop canopy, the spray rod is adjusted to maintain the optimum distance from the crop canopy by control. As shown in Figure 9, when the spray rod passes over the crop, the distance between the spray rod and the crop canopy is maintained at the set value D_s.

In the area from point A to point B, when the set value D_s is equal to the distance value D_C measured by the ultrasonic sensor between the spray rod and the crop canopy, the spray rod remains in its current state. When the set value is greater than the measured distance value, the spray rod rotates upward; when the set value is less than the measured value, the spray rod rotates downward.

At the same time, during the 3-5 leaf stage, the ultrasonic sensor can measure the distance between it and the ground D_G. In the area without crops from point B to point C, the distance values measured by the ultrasonic waves, D_C and D_G, are basically equal. At this time, D_G is also basically equal to the measured value of the distance between the ultrasonic wave and the ground in the previous cycle. Therefore, it is considered that there are no crops under the current ultrasonic ranging sensor. Usually, the measured distance $D_C > D_S$, so the spray rod needs to be lowered according to the control requirements. If the spray rod is lowered, it is likely that the crops will collide with the agricultural machinery as the sprayer continues to move forward, damaging both the machinery and the crops. Therefore, when there is an area without crops, a virtual Dc' is fed back to the control system.

$$D_c' = D_g - (D_{g1} - D_{c1}) \tag{2}$$

where:

D_c' is the distance from the ultrasonic sensor to the crop canopy in the virtual crop-free area, m;

D_g is the distance between the ultrasonic sensor and the ground during the current sampling period, m;

D_{g1} is the distance between the ultrasonic sensor and the ground during the most recent sampling period ($Dg > Dc + hr$), m;

D_{c1} is the distance between the ultrasonic sensor and the crop canopy during the most recent sampling period ($Dg > Dc + hr$), m.

By assuming that the current crop height is the same as the crop height collected in the previous cycle, the current state of the boom is maintained. When the boom runs over the crop again, in the area between point C and D, the boom continues to maintain a parallel state with the crop canopy, as shown in Figure 8 (*Strelioff et al., 2014*).

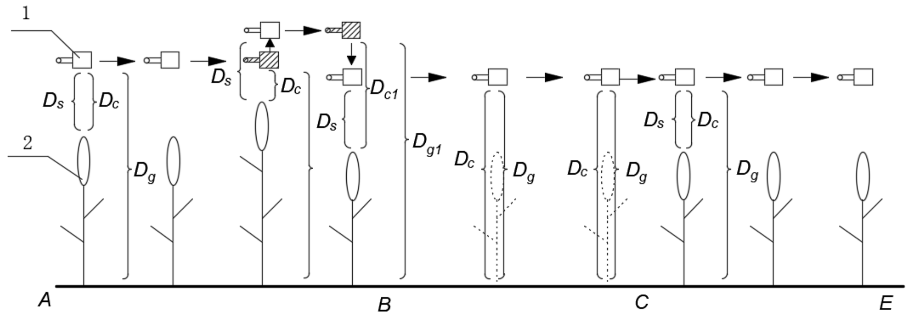


Fig. 8 - Algorithm for sparse branches and leaves

1. Ultrasonic sensor; 2. Crop

As the crop grows, after the 6-leaf stage, the corn branches and leaves become more abundant, making it difficult for ultrasonic waves to reach the ground, as shown in Figure 9. When the monitoring target remains the same, which is the distance between the boom and the crop canopy, in the area between point A and B, the system compares D_C and D_S and controls the angle of the boom. At this time, the measured D_G value is very small, and according to Equation (2), the current D_G value cannot be measured.

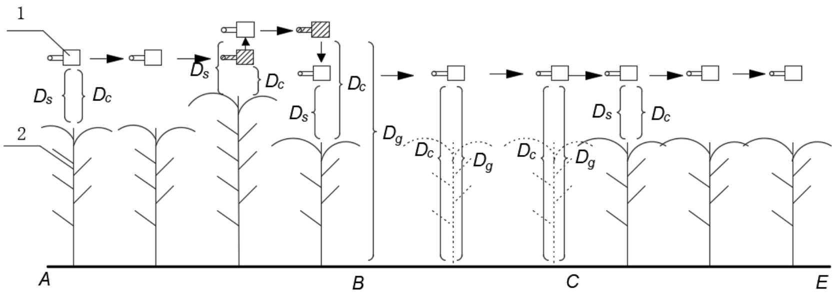


Fig. 9 - Algorithm for dense branches and leaves

1. Ultrasonic sensor; 2.Crop

When the boom enters the area BC, which is a region without crops, from the region AB where there are crops, the ultrasonic sensor near point B can collect both the distance to the crop canopy and the distance from the sensor to the ground. According to Equation (3), the distance between the ultrasonic sensor and the ground can be obtained. As the sprayer advances, when (D_G - D_C)<h_r, it can be assumed that this area is a region without crops. By using Equation (3), the distance between the ultrasonic sensor and the ground is virtually generated and then fed back to the control system.

$$D_g = \begin{cases} D_g & D_s + H_p - h_r \leq D_g \leq D_s + H_p + h_r \\ 0 & D_g < D_s + H_p - 25 \end{cases} \tag{3}$$

where:

D_G is the distance between the ultrasonic sensor and the ground during this sampling cycle, measured m. D_S is the distance between the sensor and the crop canopy set by the system, measured, m. H_P is the average height of the current crop, measured, m. h_r is the height of the crop ridge, m.

Vehicle body angle filtering algorithm design

When the sprayer is operating in the field, the main external excitation sources are high-frequency pulse signals and low-frequency step signals. When the wavelength is greater than 20 m and the vehicle forward speed is 2 m/s, the oscillation frequency of the vehicle is less than 0.6 rad/s. The boom should be able to fully track the ground fluctuations, and the boom can follow the vehicle's oscillation. When the oscillation frequency of the vehicle is higher than 5 rad/s, the ratio between the boom angle and the ground angle should be less than 0.2.

In order to eliminate high-frequency signal noise interference, the sampled signal is subjected to Fourier transformation to obtain the frequency of the current signal, and then signals with frequencies greater than 1 Hz are filtered out. The controller collects data N from the tilt angle sensor, applies Fourier filtering to calculate the current roll angle of the vehicle, and compares the current roll angle γi with the roll angle at the last actuation of the electro-hydraulic push rod. If equation (4) is satisfied, the roll angle of the current sampling period is sent to the PC by the controller.

$$|\gamma_i - \gamma_0| > \delta \tag{4}$$

where: γ_0 is the inclination angle of the vehicle at the last actuation of the electro-hydraulic push rod. γ_i is the inclination angle of the vehicle during the i-th sampling period. δ is the threshold value, and in the design, δ = 0.5.

Algorithm design for boom angle

By using the distances measured by ultrasonic sensors installed on both sides of the boom and the distance between the two sensors, the angle γ_u of the boom relative to the crop canopy or ground can be calculated. The vehicle inclination angle γ obtained from the dynamic inclination sensor data after Fourier filtering. When only the former is used as the input to the control system, vibrations caused by field ground excitation can lead to erroneous actions by the control system. When only the latter is used as the input to the control system, the system can only receive the current angle information of the boom, lacking the height of the boom relative to the crop canopy. Therefore, combining both inputs, the specific algorithm is as follows:

$$\gamma_b = \begin{cases} \gamma_{b0} & |\delta_\gamma| < \delta \\ \gamma_u & |\delta_\gamma| \geq \delta \end{cases} \tag{5}$$

where:

δ_γ represents the rate of change of the vehicle inclination angle γ; δ is the threshold value, and the optimal value is obtained through multiple experiments.γ_{b0} is the boom angle of the previous cycle.

Communication protocol and related design

In order to enable serial communication and control of agricultural machinery, the International Organization for Standardization (ISO) developed ISO 11783 based on the CAN 2.0B bus. ISO 11783 is a communication protocol that operates on top of the physical and data link layers (*Gao et al., 2019*). While the CAN 2.0B bus protocol includes both standard data frame and extended data frame formats, ISO 11783 specifically defines a complete communication standardization strategy for the extended data frame format. Therefore, this paper utilizes the extended frame format.

The extended frame format adopts the Protocol Data Unit (PDU) standard data frame format, as shown in Figure 10, which mainly includes priority (P), extended data page (EDP), data page (DP), PDU format (PF), specific PDU (PS), and source address (SA)(*Ding et al., 2019*). Referring to the ISO 11783 standard, a 29-bit identifier is defined for the spray boom control system, and the specific parameters for the 29-bit identifier are defined as shown in Table 1.

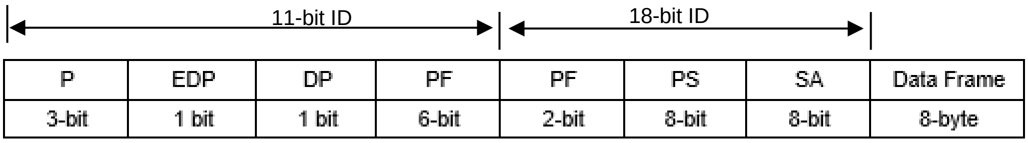


Fig. 10 - ISO 11783 PDU

In order to reduce the overhead of processing CAN signals by the processor, the following settings are made for the filter registers and mask registers, as shown in Table 2.

Table 1

Parameter definitions for 29-bit identifiers

Name	P	EDP	DP	PF	PS	SA
left	6	0	0	FE	FF	F4
right	6	0	0	FC	FF	F2
PC	3	0	0	F0	FF	00
electric actuator	6	0	0	FB	FF	F1
vehicle tilt angle	6	0	0	FA	FF	05

Table 2

Setup of CAN bus

Name	Frame format	ID	Masking filtering	Mask register	Filter register
left	Extended frame	63FEFFF4	Mask bit mode	00C00000	00F300FF
right	Extended frame	63FCFFF2	Mask bit mode	00C00000	00F300FF
PC	Extended frame	33CCFF00	Disable filtering	—	—
electric actuator	Extended frame	63EFFFF1	Mask bit mode	00C00000	00F300FF
vehicle tilt angle	Extended frame	63EEFF05	Mask bit mode	00C00000	00F300FF

In the system, the PC can not only directly read the values of each node on the CAN bus but also send commands directly to the node controlling the electric actuator. This mainly includes parameters such as the extension/retraction direction of the electric actuator and the duty cycle of the PWM waveform used to control the electric actuator.

Human-machine interface software design

To achieve real-time detection and control of the spray boom angle, this paper utilizes VC++6.0 to develop a PC program, as shown in Figure 11. The PC is responsible for receiving and sending data, analysing, processing, calculating control variables, and storing information. Each node sends the collected parameters to the PC in real-time.

The PC saves the measured distance data and vehicle tilt angle information into a database. It also uses the fuzzy ISODATA method to analyse and obtain the height of the spray boom relative to the crop canopy. The PC applies Fourier transform to filter out signals greater than 1Hz from the vehicle tilt angle. By using the distance information between the left and right spray booms and the filtered vehicle tilt angle, the current tilt angle of the spray boom is obtained. The current vehicle tilt angle serves as an input parameter. With the appropriate control algorithm, the PC determines the extension/retraction direction and the duty cycle of the input waveform for controlling the electric actuator.

The PC interface includes four sections: the main operating interface, system parameter settings, communication port settings, and data display.

The parameters that need to be set before the system runs are shown in Figure 12. First, select the operation mode. When herbicides need to be sprayed on corn during the 3-5 leaf stage, it is necessary to identify the distance between the spray boom and the ground and select 'Ground Mode'. When conducting pest and disease control, the distance between the spray boom and the canopy needs to be identified, and 'Canopy Mode' should be selected. Spray height refers to the distance between the spray boom and the canopy or ground. Due to the different targets and modes of action of pesticides, the appropriate height from the spray nozzle to the target may vary. Therefore, it is necessary to set the spray height before conducting spraying operations. The distance between the two ultrasonic sensors refers to the straight-line distance between the installation positions of the two ultrasonic ranging sensors. It is one of the parameters used to calculate the tilt angle of the spray boom.

Adjusting the threshold refers to adjusting the threshold value of the relative distance between the two ends of the spray boom and the spray target in the spray boom angle control. The system parameters that are set will be saved in the database and displayed on the main operating interface.

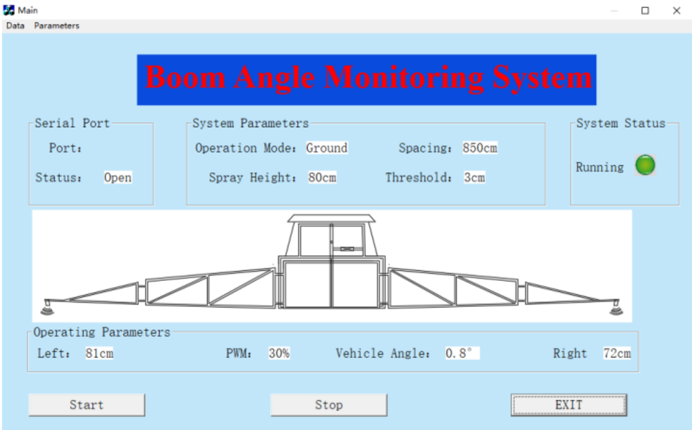


Fig. 11 - Main interface

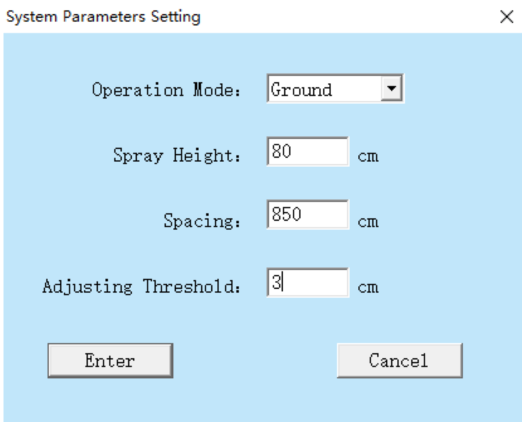
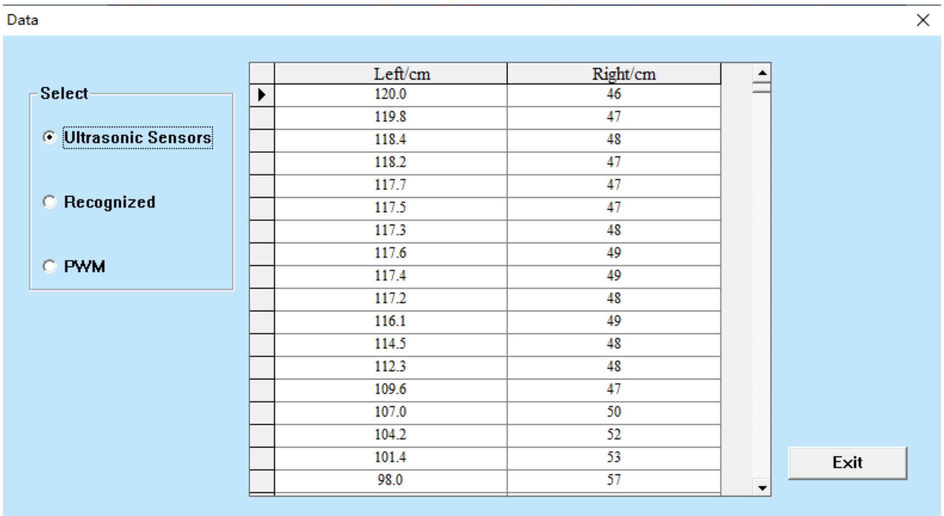


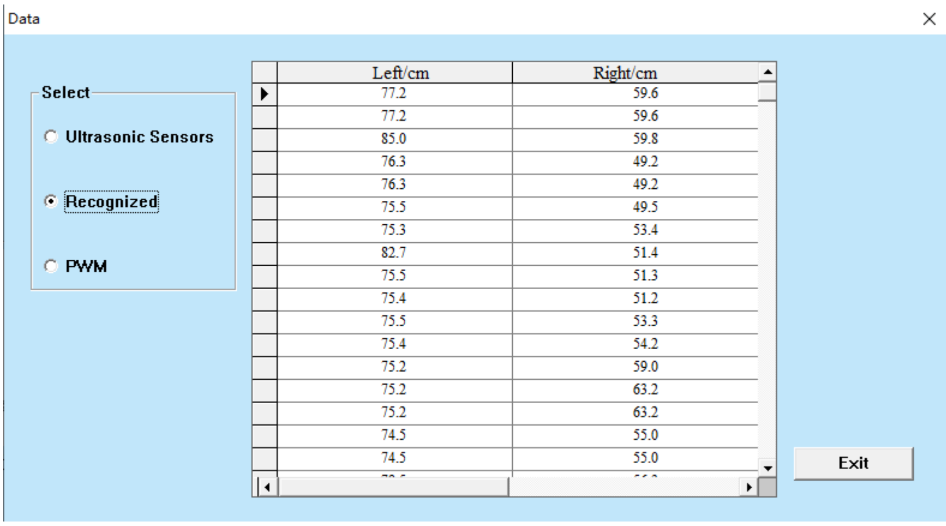
Fig. 12 - System parameters setting interface

RESULTS

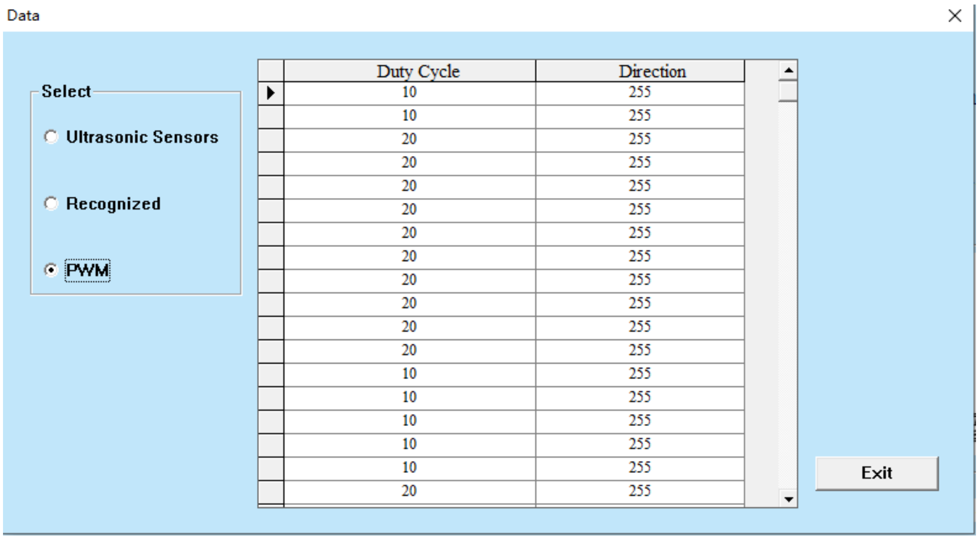
In order to verify whether the design of the boom inclination control system is reasonable, the system is installed on the boom whose length is 9 m to measure the distance from the boom to the ground. After the system is running, the data shows that the menu can be used to view the collected data, the data clustered during the operation, and the control data during the system operation, as shown in Fig.13.



（a） Ultrasonic sensor measurement data



（b） Clustered data



（c） Control data

Fig. 13 - Data display

CONCLUSIONS

According to the control requirements, a spray boom tilt control system based on the CAN bus was constructed, which consists of a main control node, distance measurement nodes, vehicle tilt detection nodes, and tilt control nodes. An ultrasonic sensor is used to measure the distance between the spray boom and the crop canopy or ground, a tilt sensor is used to measure the vehicle tilt angle, and an electric actuator is used to achieve real-time automatic control of the spray boom angle. The detailed design methods for the hardware and software of the real-time control system for the spray boom angle are described.

The design of a serial communication network based on the CAN bus has been completed, and the bus communication protocol for the spray boom tilt control system has been developed according to the ISO 11783 standard. This is beneficial for the standardized transmission of spray boom angle control parameters and system expansion in the future.

For the canopy mode and ground mode, a real-time dynamic monitoring system for spray boom angle was designed, which displays various parameter information in the spray boom tilt control system in real-time. The system has functions such as displaying and setting system parameters, browsing data, and automatically monitoring the tilt angle of the spray boom and making decisions based on the detection information. It drives the electric actuator to work and has a user-friendly and easy-to-operate human-machine interface.

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