DESIGN AND STUDY ON THE ADAPTIVE LEVELING CONTROL SYSTEM OF THE CRAWLER TRACTOR IN HILLY AND MOUNTAINOUS AREAS
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丘陵山区履带式拖拉机自适应调平控制系统的设计与研究

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ABSTRACT

In order to improve the automation level of the crawler tractor leveling system, an adaptive leveling control system was designed for the developed crawler tractor leveling device. The overall hardware of the leveling control system was determined and the software system of the leveling device was designed using the proportional algorithm. The designed leveling control system is composed of the real-time detection part, control part, driving part and display part. The system can realize the real-time detection of the tractor inclination angle, and complete rapid leveling of the leveling device. The test results of the leveling control system show that the leveling accuracy and leveling time of the lateral and longitudinal slope increase with the increase of the tractor inclination angle. The leveling accuracy and stability of the longitudinal slope are better than that of lateral slope leveling, and the leveling speed is higher than that of the lateral slope. The coordination leveling accuracy is higher than the independent leveling accuracy of the lateral slope and longitudinal slope, and the collaborative leveling accuracy of the longitudinal slope is better than that of the independent leveling accuracy. The developed leveling control system can independently complete the leveling work under the actual working conditions of the crawler tractor. The leveling accuracy can be in 1° and the leveling time is in 0-6 s. The leveling accuracy and time can meet the design requirements.

摘要

为了提高履带式拖拉机调平系统的自动化水平,针对开发的调平装置进行了自适应调平控制系统的设计与研究。设计了调平装置控制系统硬件设备的整体方案，并采用比例算法对调平控制系统的软件部分进行了设计。设计开发的调平控制系统主要由实时检测部分、控制部分、驱动部分及显示部分组成。通过该系统能够实现对拖拉机作业中车身倾斜角度的实时检测，并基于检测信息实现调平装置的快速调平。调平控制系统性能测试结果表明：系统在调平作业中横坡、纵坡调平精度及时间均随车身倾角增加而增加，纵坡调平精度及平稳性均好于横坡调平、调平速度高于横坡调平，协同调平中横坡、纵坡调平精度较横坡、纵坡独立调平精度均有所提升，纵坡协同调平精度明显优于其独立调平精度，同时调平控制系统能够根据机具实际作业情况自主完成调平工作，调平精度均能达到 1° 以内，调平时间在 0-6s 以内，调平精度及时间均能满足设计要求。

INTRODUCTION

In Hilly and mountainous areas, the working quality and mechanization level of machines are reduced due to large topographic conditions, and the machine is at risk of overturning. In recent years, researchers have done a lot of research on the automatic leveling technology of agricultural tractors, mainly through the processing of external information to realize the automatic leveling of tractors *(Li et al., 2021; Li et al., 2019; Pijuan et al., 2012; Wang et al., 2021; Wang et al., 2019).* The early leveling system was mainly controlled by the integrated circuits, and many advanced technologies were gradually introduced *(Kwon et al., 2020; Marcelo et al.,2018; Pawin et al., 2016; Phu et al., 2020; Rabiet al., 2020; Yin et al., 2020). Qi et al., (2019)* designed an autonomous adjustment system for tractors in Hilly and mountainous areas.

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This system used the PID and closed-loop fuzzy PID algorithms to effectively reduce the overshoot and leveling time. Zhang, *(2019)* designed a leveling system of parallel four-bar mechanism for the power chassis of agricultural machinery in Hilly and mountainous areas. The system takes PLC (programmable logic controller) as the control core and uses electromagnetic proportional control valve to control the expansion and contraction of the hydraulic cylinder. *Peng et al., (2018) and Wang et al., (2017)* designed a four-point hydraulic support and hydraulic driven leveling system for hilly and mountainous wheeled tractor. This control system adopts fuzzy PID control algorithm to realize the leveling of the device. Moreover, *Xu et al., (2017)* designed an automatic leveling system controlled by PLC, and the inclination sensor was used to detect the tractor inclination. PLC was used to control the expansion and contraction of the hydraulic cylinders on both sides of the tractor to drive the parallel four-bar mechanism and complete the real-time leveling. The leveling control system of the leveling device designed in this paper can detect the road conditions and process dates in real time. It meets the requirements of leveling accuracy and response time under the normal operation conditions of the leveling control system.

MATERIALS AND METHODS

OVERALL SCHEMES AND WORKING PRINCIPLE

The overall scheme of the leveling control system is shown in Figure 1, including detection part, control part, driving part and display part.

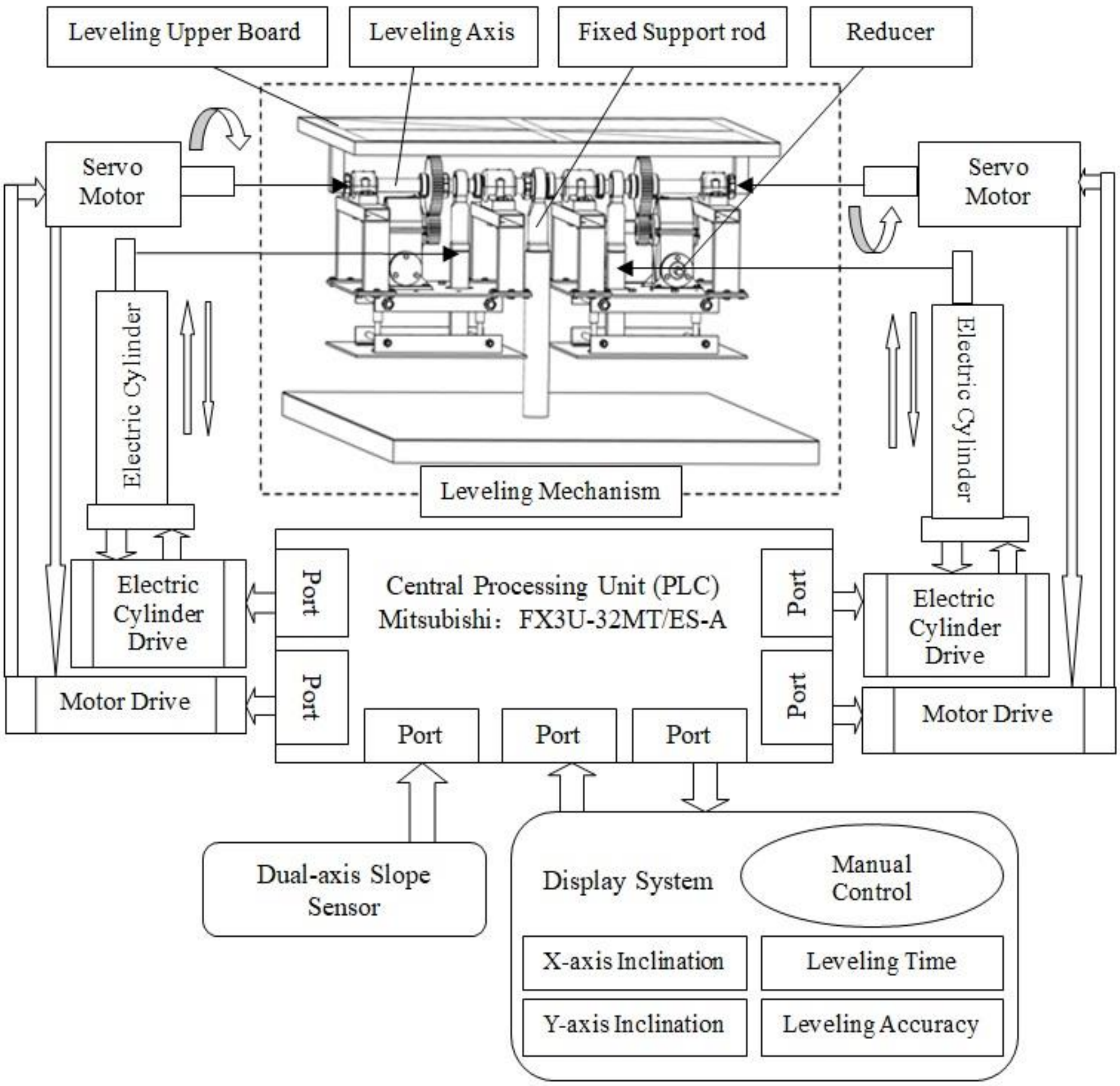


Fig. 1- Overall scheme diagram of the leveling control system

The tractor battery converts 12V DC into 220V AC via an inverter to power the entire leveling control system. In the detection part, the inclination of the tractor is detected by the dual-axis inclination sensor and fed back to the control system for real-time processing. The leveling is realized by driving the servo motor and servo electric cylinder in real time. The display part mainly monitors the working conditions of the leveling system in real time, and displays the inclination angle of the lateral slope and longitudinal slope of the leveling device, as well as the leveling time and leveling accuracy. The leveling control system is divided into manual control and automatic control. The manual control is realized through the human-computer Interactive function of the display. It is mainly to level one side separately when there is a problem with the leveling system or special circumstances, if system is stopped in case of an emergency. The leveling mechanism is mainly composed of the longitudinal and lateral slope leveling mechanism. The longitudinal slope direction is controlled by the rotation of the servo motor, and the lateral slope direction is controlled by the expansion and contraction of the servo electric cylinder. These two parts are adjusted independently. During the leveling process, the servo motor and servo electric cylinder are automatically leveled with the inclination angle of the tractor in real time, so as to keep the tractor within the preset inclination range. The machines and tools are installed on the leveling upper plate when operating. The leveling control system detects the inclination angle of the tractor through the dual-axis inclination sensor in real time, and transmits the detection information to the central processing unit (PLC) through the data line. The PLC controller processes the detected real-time inclination angle signal through the control algorithm, and sends the result command to the driving part in real time. The servo motor drives the horizontal axis to rotate radially through the reducer to complete longitudinal adjustment. The servo driver controls the expansion and contraction of the left and right electric cylinders and drives the leveling shaft to swing axially to complete the lateral adjustment.

DESIGN OF LEVELING CONTROL SYSTEM

CONTROL ALGORITHM

The leveling control system adjusts the speed by controlling the expansion of the servo electric cylinder and the servo motor to complete the tractor leveling. The proportional algorithm is used for the designed control system, and the inclination angle (*a*) of the tractor is used as the control parameter. The leveling accuracy error is *e*, and the output parameter is the servo motor speed *n*. The longitudinal slope is the forward direction of the tractor in the Y-axis direction, and the lateral slope is the forward vertical direction of the tractor in the X-axis direction. The leveling accuracy of the longitudinal slope is set in $-1° < a_y < 1°$, and that of the lateral slope is in $-1° < a_x < 1°$. $a(t)$ is the inclination angle function of the tractor, which is the input function of the proportional controller. $e(t)$ is the error function, and $n(t)$ is the speed function of the servo motor, which is the output function of the proportional controller. During the sampling period, the error function is as follows:

$$e(t)=\begin{cases} a(t)-1^{\circ} & (a(t)\geq 0) \\ a(t)+1^{\circ} & (a(t)<0) \end{cases} \tag{1}$$

After calculation, the speed function of the longitudinal slope leveling servo motor is

$$n_y(t)=\frac{1}{6}k_1 e(t)=\begin{cases} \frac{1}{6}k_1 e[a_y(t)-1^{\circ}] & (a_y(t)\geq 0) \\ \frac{1}{6}k_1[a_y(t)+1^{\circ}] & (a_y(t)<0) \end{cases} \tag{2}$$

The speed function of the servo electric cylinder is:

$$n_x(t)=\frac{1}{6}k_2 e(t)=\begin{cases} \frac{1}{6}k_2 e[a_x(t)-1^{\circ}] & (a_x(t)\geq 0) \\ \frac{1}{6}k_2[a_x(t)+1^{\circ}] & (a_{yx}(t)<0) \end{cases} \tag{3}$$

where: k_1- the preset ratio of the longitudinal slope function;

k_2- the preset ratio of the lateral slope function.

During the control process, the sensor detects the inclination range of the tractor. The real-time inclination angle of the tractor is displayed on the screen, and it is determined whether the inclination angles in the Y-axis and X-axis directions are in the set accuracy range. When the inclination angle is not in the accuracy range, the inclination angle a_y (or a_x) is input into the proportional controller for proportional calculation. The calculated signals are transmitted to the servo motor driver or servo electric cylinder driver to control the movement of relevant leveling mechanism. The leveling is not ended until the leveling accuracy requirements are met. The flowchart of the leveling control system is shown in Figure 2.

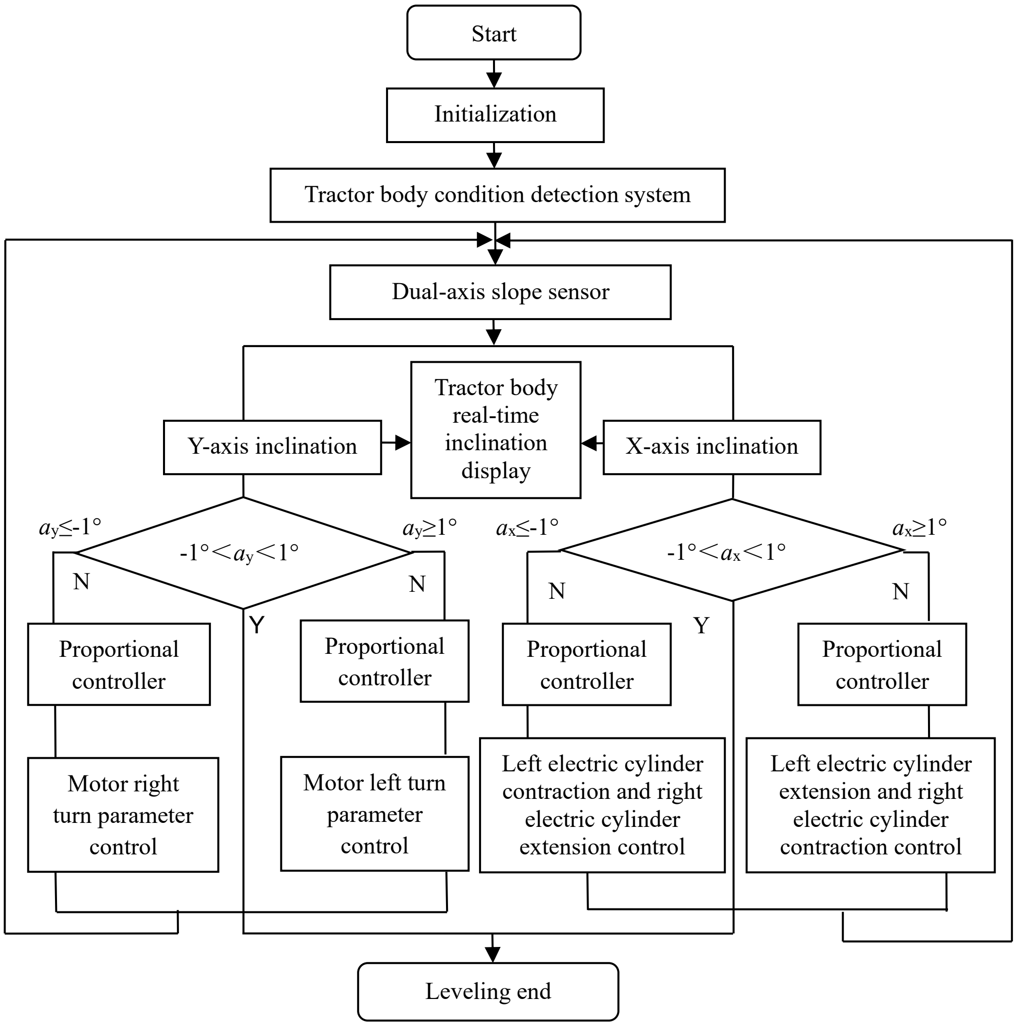


Fig. 2 - Program flow chart

PLC CONTROLLER

According to the design requirements of the control system, PLC adopts Mitsubishi FX3U-32MT/ES-A with transistor output. The PLC port is shown in Figure 3.

X_0 is set as the emergency switch to control the main switch and emergency stop of the leveling system. X_1 is set as the longitudinal slope leveling switch to control the servo motor, X_2 as the lateral slope leveling switch to control the servo electric cylinder.

Y_0 is set as pulse 1 (the pulse sending interface of the servo motor). Y_1 is set as pulse 2 (as the pulse sending interface of the servo electric cylinder). Y_5 is set as enable 1 with opening and closing port (the enable opening or closing interface of the servo motor). Y_6 is set as direction 1 with positive and negative port (the positive and negative direction control interface of the servo motor). Y_{10} is set as enable 2 with opening and closing port (the enabling opening or closing interfaces of the servo electric cylinder driver). Y_{11} is set as the positive and negative change port of direction 2 (the positive and negative direction control interface of the servo electric cylinder driver).

The pulse 1, enable 1 opening and closing, direction 1 positive and negative of the PLC ports are set as the driving programming wiring port of servo motor, which can control the longitudinal slope leveling and the opening and closing state of the servo motor. The pulse 2, enable 2 opening and closing, direction 2 positive and negative of the PLC ports are set as the driving programming wiring port of the servo electric cylinder, which can control lateral slope leveling and the opening and closing state of the servo electric cylinder.

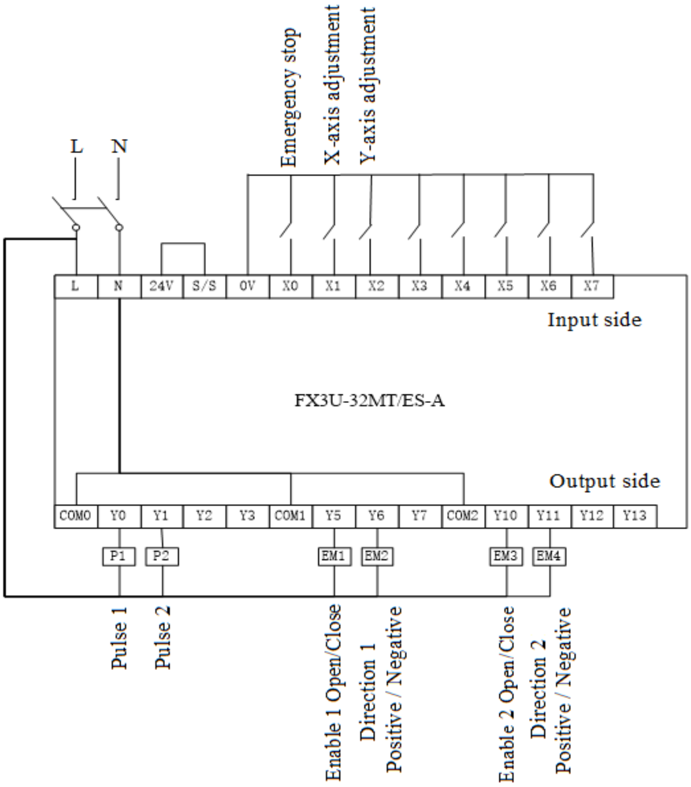


Fig. 3 - PLC port settings

SERVO MOTOR AND DRIVE

The drive controls the servo motor to adjust the longitudinal slope. According to the design requirements, the motor driver adopts MBDLN25SE and the servo motor adopts MSMF042L1U2M. The leveling system adopts the position control mode, and the connection between the driver and peripheral equipment is shown in Figure 4.

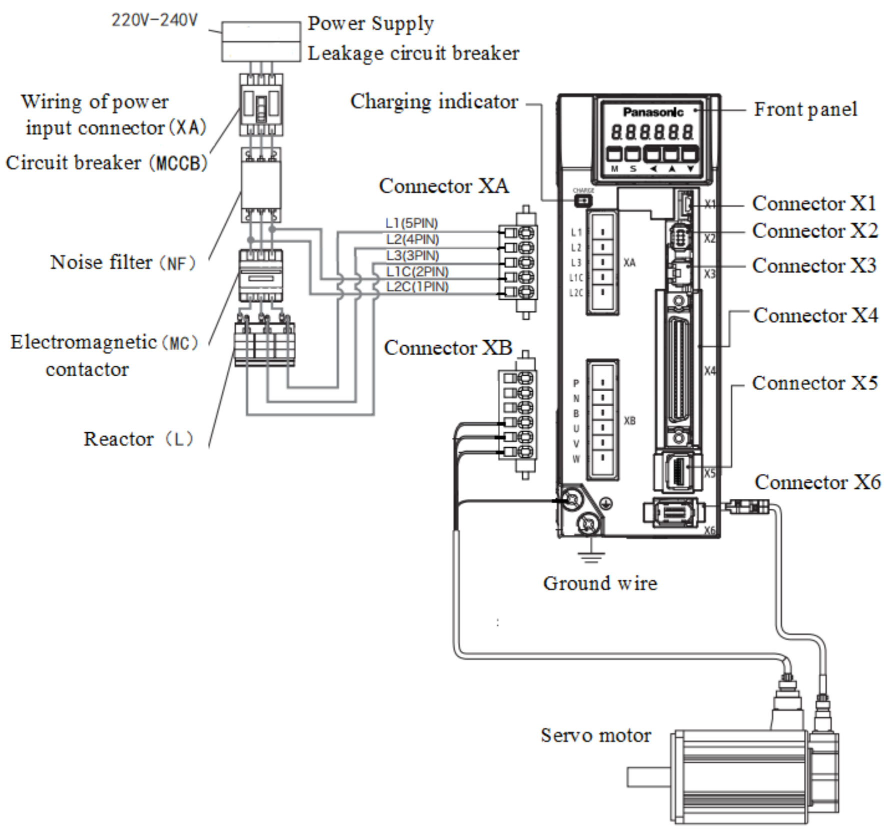


Fig. 4 - Motor driver and peripheral equipment connection diagram

The connector X_A on the driver is the wiring of the power input port, and the power line is protected by the circuit breaker. The noise interference from the driver is reduced by the noise filter, and the electromagnetic contactor is used to connect or disconnect the main power supply of the driver. In addition, the reactor is also used to reduce the high-order harmonic current of the power supply. Connector X_B and X_4 are connected with the servo motor and the coding line of the servo motor, respectively, and the connector X_4 is used to control the coding of the servo driver. Before leveling programming control, the motor should be tested to check the working state of the driver. First, the connector X_4 is connected and the power supply of the driver is turned on to confirm the standard setting value of the parameter. Then, "on state" of the servo is set and the motor is put in the excitation state. Finally, the low-frequency pulse signal from the upper device is input to make the motor run in low-speed, and the motor speed is confirmed in monitoring mode.

SERVO ELECTRIC CYLINDER AND DRIVE

The driver controls the servo electric cylinder to adjust the lateral slope. According to the design requirements, the driver adopts DS3E-21P2-PFA and the servo electric cylinder adopts MS-1100ST-M04030BZ-21P2. The leveling control system adopts the position control mode, and the leveling control uses single phase AC electrical 220V. The power wires are connected to the R and T interfaces, and the wiring ports of the driver are connected with the corresponding terminals of the electric cylinder. The built-in resistance is used for the regenerative resistance terminal, short circuit P+ and D terminals, disconnect P + and C, and p_0-24=0. CN_0 is input and output signal terminal of the pulse, direction and enable, and it is also the coding line interface of the driver. CN_0 is connected with PLC to control the driver coding. CN_1 terminal is used for expansion module. CN_2 is the driver encoder terminal and connected with the coding line of the servo electric cylinder. The connection between the driver and peripheral equipment is shown in Figure 5. CN_0 terminal is connected with PLC, and terminal 1 and terminal 4 are respectively used as the pulse and direction inputs to control the expansion and contraction speed of the electric cylinder. SI1 terminal is used as the enabling input and the switch of the electric cylinder.

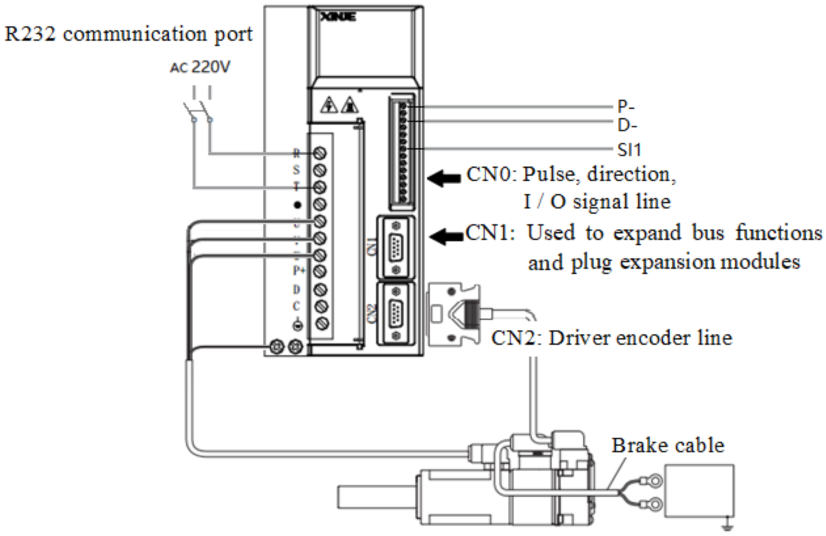


Fig. 5 - Electric cylinder driver and peripheral equipment connection diagram

INCLINATION DETECTION PART

The inclination detection circuit is used to detect and feedback the inclination angle of the tractor. The detection element adopts dual-axis inclination sensor HVT826T, and the wiring is shown in Figure 6. The output interface of the sensor is 5 lines. Two lines are the power lines, where the red is the positive line of power supply (AC11~36V), and white is the negative line of power supply. The black is the grounding wire, and yellow and green are the communication lines. The yellow send data terminal (TXD) is connected the receive data interface (RXD) of the PLC communication. The green receive data terminal (RXD) is connected the send data interface (TXD) of the PLC communication. Before using the inclination sensor, the power test and parameter setting are carried out. The corresponding product model HVT826T and the corresponding COM port of the equipment are selected to open the software interface.

The current address code of the sensor is 00, and the current baud rate of the sensor is selected as 9600 bit/s. Then the corresponding parameters are set for initialization and information detection. When the leveling control system works, the PLC sends the inclination reading command. The sensor verifies whether the command is correct and then sends the inclination information, which is the compressed BCD code. The PLC needs to read the inclination values of lateral slope and longitudinal slope according to the BCD code reading rules. In the communication program, the PLC uses the timer T command to read the inclination information once, and then the inclination information is read through RS command and the sensor communicating. The maximum output frequency of the sensor is 50Hz, and the sampling period is 80ms.

Fig. 6 - Sensor wiring diagram

DISPLAY PART

According to the design requirements of the leveling control system, the display is Xinjie OP320-A-S. The display operation interface is designed by the editing software "Xinjie 6.5". During the display programming, the USB-to-RS232 driver is installed on the PC port and the display is connected with the PC port. The corresponding display model OP320-A-S in the editing software is selected and the communication type "Mitsubishi (FX) between the display and PLC. Then the display content is written. The display interface includes emergency stop switch, lateral slope adjustment switch, longitudinal slope leveling switch, real-time inclination angle, current leveling time and historical leveling time. The display is connected with PLC 485-BD communication port through the BD9-pin serial port line to realize communication with PLC. Before the display works, it is necessary to set PLC communication to ensure that the communication format between the display and PLC is consistent. Through the buttons on the operation interface, the leveling of Y-axis and X-axis directions of the tractor can be controlled manually, so as to realize the independent axis direction leveling test, clear historical data and register cached data.

PERFORMANCE TEST OF LEVELING CONTROL SYSTEM

CONTENT AND METHOD

When the tractor was driving in the experimental field of Sichuan Agricultural University, the accuracy and time of the leveling control system were tested for the tractor inclination. The developed adaptive leveling system is shown in Figure 7.

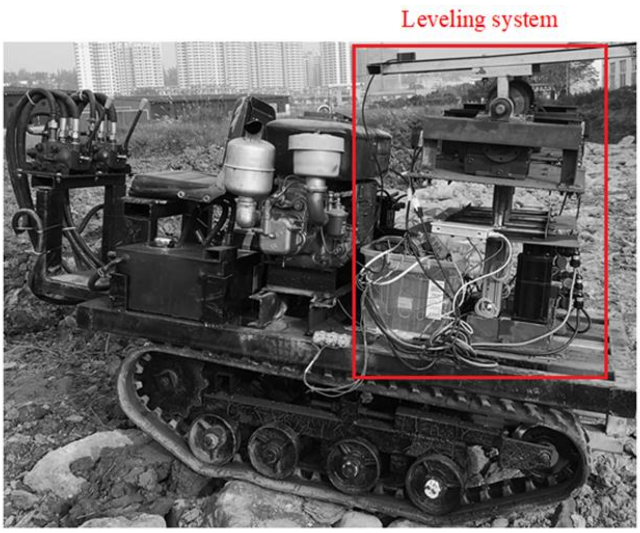


Fig. 7 - The adaptive leveling system testing prototype

The testing is divided into three groups: (1) Independent leveling performance of the longitudinal slope; (2) Independent leveling performance of the lateral slope; (3) Coordinated leveling performance of lateral slope and longitudinal slope. Before each testing group, the leveling device was set on the horizontal plane, so that the angles of the lateral slope and longitudinal slope were 0°. In the first testing group, the lateral slope leveling switch was off to test the independent leveling accuracy and time of the longitudinal slope of the system. In the second testing group, the longitudinal slope leveling switch was off to test the independent leveling accuracy and time of the lateral slope of the system. In the third testing group, the leveling switches of the lateral slope and longitudinal slope were set "on state" to test the leveling accuracy and time of the coordinated leveling of the system.

RESULTS AND ANALYSIS

During the test, the dual-axis inclination sensor was used to test the inclination angles of the tractor in the directions of the lateral slope (X-axis) and longitudinal slope (Y-axis). The inclination angles are recorded and processed in real-time, and the leveling (leveling accuracy) and leveling time are displayed on the screen at the same time. The test results are shown in Table 1, Table 2 and Table 3.

Table 1

X-axis leveling test results

Absolute value of X-axis slope /°	Absolute value of leveling accuracy /°	Leveling time /s
3.45	0.49	0.97
7.63	0.69	1.63
9.88	0.55	2.87
12.04	0.85	3.75
14.13	0.96	4.98

Table 2

Y-axis leveling test results

Absolute value of Y-axis slope /°	Absolute value of leveling accuracy /°	Leveling time /s
5.49	0.69	0.85
8.99	0.72	1.48
14.16	0.76	2.68
18.78	0.93	3.25
22.55	0.98	4.13

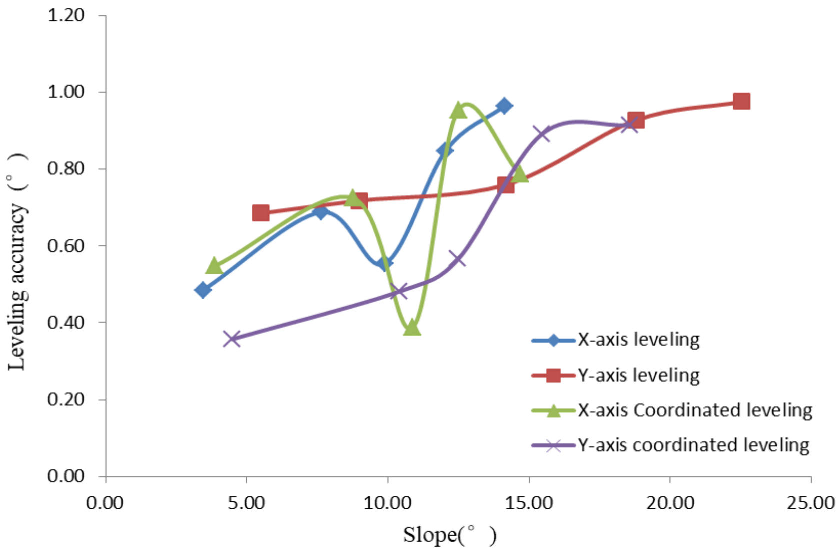
Table 3

X-axis and Y-axis coordinated leveling test results

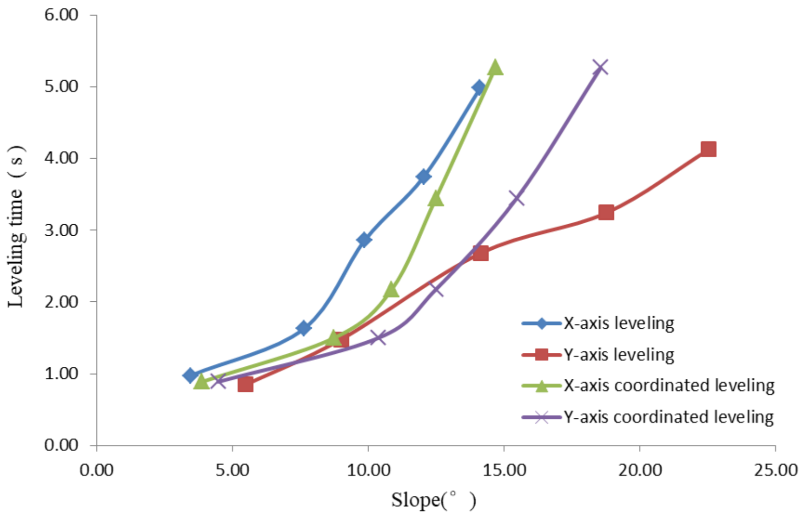
Absolute value of slope /°		Absolute value of leveling accuracy /°		Leveling time /s
X-axis	Y-axis	X-axis	Y-axis	
3.88	4.48	0.55	0.36	0.89
8.75	10.38	0.73	0.48	1.50
10.86	12.47	0.39	0.57	2.17
12.49	15.47	0.95	0.89	3.45
14.68	18.56	0.79	0.92	5.27

It can be seen from the results that the designed leveling control system can maintain the leveling accuracy within 1° under no-load conditions, and the leveling time is between 0 and 6s. The performance parameters of the leveling control system can usually meet the objectives and requirements of the system design. Nevertheless, the self-vibration of the tractor in operation will increase the leveling time, and result in the overshoot of the system and oscillation around the leveling angle. From Figure 8, it can be seen that during the leveling, the leveling accuracy and leveling time of X-axis and Y-axis increase with the increase of the tractor inclination. The leveling accuracy and stability of Y-axis are better than that of X-axis, and its leveling speed is higher than that of X-axis. The collaborative leveling accuracy of X-axis and Y-axis is higher than the independent leveling accuracy of X-axis and Y-axis. The collaborative leveling accuracy of Y-axis is significantly better than its independent leveling accuracy, and the collaborative leveling speed of X-axis and Y-axis slopes is lower than that of X-axis slope. The reason is that the vibration of the tractor has a great impact on the inclination signal detected by the inclination sensor.

The control system cannot effectively filter the noise model of the tractor, and the vibration of the tractor has a great impact on the electric cylinder in the leveling system. The Y-axis leveling is controlled by the servo motor through the reducer with self-locking function to reduce the accumulation of errors during the leveling process. The motion conversion efficiency of the servo motor is also higher than that of the servo electric cylinder. As such, the real-time operation can be completed accurately and in time, and the influence of over-leveling and vibration can be effectively prevented. The interaction between the leveling of X-axis and Y-axis is significant, and the collaborative leveling can effectively improve the effect of the control system.



(a) Leveling accuracy
(b)



(b) Leveling time

Fig. 8 - Change chart of leveling time with variable frequency parameters

CONCLUSIONS

(1) The system adopts the Mitsubishi FX3U-32MT/ES-A as the core of the signal processing and control system, and uses the double axis inclination sensor HVT826T to detect the inclination of the tractor. The designed leveling control system adopts the position control mode, and the servo motor is controlled by the driver to adjust the longitudinal slope, so as to adjust the lateral slope and the servo electric cylinder. The display OP320-A-S is adopted. Through the editing software "Xinjie 6.5", the design of the display interface of the leveling control system and the real-time communication function with PLC are completed on the computer. The basic test parameter display and human-computer interactive functions of the control system are realized.

(2) The test results of the leveling control system shows that the designed leveling control system can work normally. Under different operating conditions, the leveling accuracy can be maintained in 1°, and the leveling time is in 0-6 s. The leveling accuracy and timeliness can meet the design objectives and requirements. The leveling control system has simple structure, good timeliness and stability. It cannot only improve the accuracy, safety and automation of the agricultural tractor, but also provide a certain theoretical basis and technical reference for improving the stability and quality of agricultural machines in Hilly and Mountainous areas.

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