Control system of a performance test-bed for frost protection wind machines

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Abstract: To test the performance and optimize operational parameters of various frost protection wind machines, a control system of performance test-bed was designed and developed based on Programmable Logic Controller (PLC) and touch screen. The system realized automatic control of operational parameters including hydraulic platform height, impeller rotation speed, depression angle, rotation range and cycle. Field case study results shows that the control accuracy of all the parameters was achieved with the average errors of 2.11 cm for height, 9.5 r/min for impeller rotation speed, 0.83° for pan-tilt rotation range and 0.061 min for rotation cycle. With the control of the test-bed, the performances of various wind machines, such as the distribution of airflow and temperature, and frost protection effect, could be tested under various working conditions, which provide experiment supports for developing wind machines adapted to different conditions with higher frost protection effect.

Keywords: frost protection, wind machines, performance test-bed, design, control, PLC
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1 Introduction

Most spring tea plants in China grow in subtropical hilly regions to the south of the Yangtze River. And as one of the most important cash crops, tea has its unique ecological and physiological characteristics, especially the sensitivity to low temperature[1]. China has been suffering severe frost damage for successive years, which resulted in sizable economic losses and unstable tea production supply[2,3]. Frost damage to crops is common in many countries, and there are more economic losses to frost damage than to any other weather-related phenomenon in the USA[4]. To fight against frost events, various mechanized equipment has been developed, among which wind machines are widely used. The working principle is to break the thermal inversion layer through air disturbance near ground, i. e., mixing warmer air aloft and cold air around the canopy with forced convection. Available models used in tea fields or orchards are elevated fan, tower wind machine, suction-exhaust duct and hovering helicopter[4-8]. These models were produced by different companies or research institutions and have been proved to be effective for preventing from radiation frosts.

However, the structure and technical specifications vary greatly among the above models, and their performance might be different. Orchard-Rite Co., Ltd. developed an orchard wind machine for frost protection, composing of a motor with power of above 90.0 kW, and an impeller with diameter of 6.0 m. And its protection

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area was about 4 hm^2 with wind machine installed at height of 10.0 m[4]. Small anti-frost fans are commonly used for tea in Japan, and the motor power is 0.75-5.0 kW, the impeller diameter is 0.6-1.2 m, installation height is 4.0-8.0 m and protection area is 0.1-0.15 hm^2. The depression angle of the fan is manually adjusted to 20°-45° and optional rotation angles are 60°, 90° and 120°[9,10]. Hu et al.[6] developed an elevated frost protection wind machine with motor power of 3.0 kW, impeller diameter of 900 mm, rotation speed of 998 r/min, installation height of 6.0 m, adjustable depression angle of 15°-50° and rotation cycle of 2 min. Wu et al.[11] designed an optimal wind machine blade through reverse engineering and simulation, which had shaft power of 2.5 kW, depression angle of 15°, forward-swept angle of 87°, hub ratio of 0.3, and arc radius of sectional circular of 1200 mm. Yang[12] developed a biconvex-airfoil wind machine prototype, which was equipped with motor power of 45.0 kW, impeller diameter of 4.44 m, rotation speed of 265 r/min, installation height of 10.0 m and installation depression angle of 14°. Wu et al.[13] designed a concave-convex airfoil for wind machine blade using Profili software. Its maximum thickness was 0.117, maximum thickness position was 0.26, maximum camber was 0.062, and maximum camber position was 0.43.

So far, there is no performance test standard for frost protection wind machines. Meanwhile, some of the operational parameters such as installation height, impeller rotation speed, depression angle, rotation range and cycle, differ with various products[14-18]. Therefore, it is necessary to develop a fully automatic test-bed and its control system to evaluate the performance and optimize technical and operational parameters for different wind machines.

2 Configuration of performance test-bed

The performance test-bed was composed of four sets of multi-stage telescopic cylinders, synchronous frame, rotatable pan-tilt, hydraulic and electric control system. Its rated load capacity was 1000 kg with maximum lifting height of 10 m, minimum retracting height of 1.97 m. Driven by double-gear oil pumps and double-drive motors, the pan-tilt could be lifted at speed of 0.033 m/s and retracted at 0.044 m/s. The configuration of the performance test-bed is shown in Figure 1.

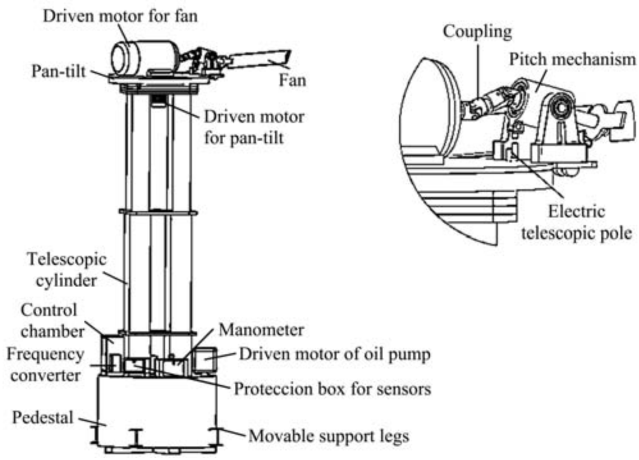


Figure 1 Configuration of performance test-bed

The pan-tilt consisted of fixed platform and auxiliary platform, which were connected by inner-tooth slewing bearing.

The pitch mechanism could change depression angle of wind machines. The wind machine motor shaft was placed inside the supporting tube, on which supporting shafts were welded symmetrically along the center of the horizontal axis for easy installation. An electric telescopic rod could change the depression angle of the wind machine through telescopic movement.

The hydraulic lifting schematic is shown in Figure 2.

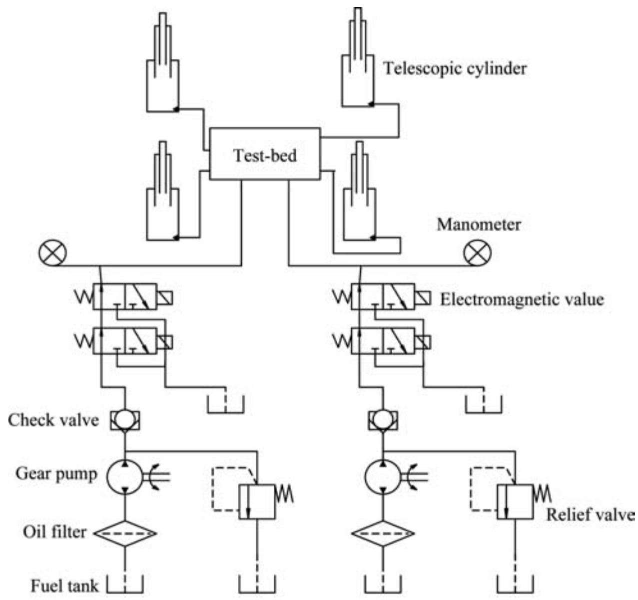


Figure 2 Schematic of hydraulic lifting system

When the oil pump started, the oil flowed into the cylinders via check valve and electromagnetic valve, which caused the piston rods to rise. When the pan-tilt reached its given height and the set pressure was attained, power supply was cut off by pressure relay or oil pressure relief. The pan-tilt went down due to its self-weight, pushing the oil into the reservoir via the electromagnetic valve. The piston rods retracted or stopped with the electromagnetic directional valves powered or not. The test-bed was under double overload protection with overload pressure relay. The control indicators of performance test-bed are listed in Table 1.

Table 1 Control indicators of performance test-bed

Operational parameter	Minimum value	Maximum value	Error range
Hydraulic platform height/m	2	10	±0.1
Depression angle/(°)	0	60	±5
Impeller rotation speed/r·min^{-1}	0	1500	–
Pan-tilt rotation cycle/min	1	10	±0.05
Pan-tilt rotation range/(°)	0	360	±1

3 Overall design of control system

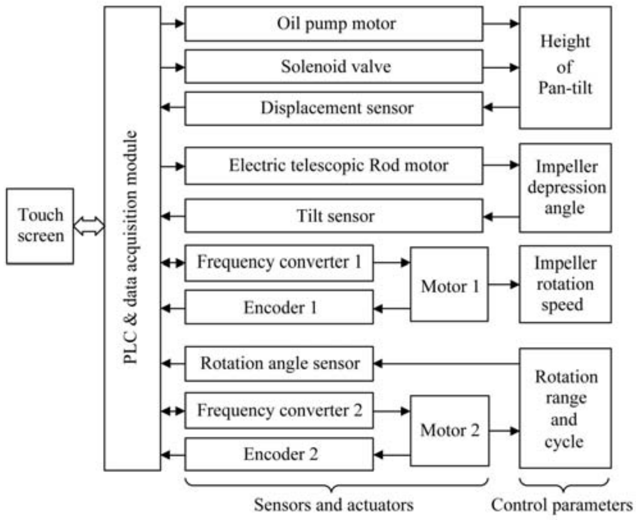
Touch screen was selected as display and input device for its field operation convenience and Programmable Logic Controller (PLC) was used as the core controller for its reliability[19,20]. The control system schematic is shown as Figure 3. The operational parameters were set on the touch screen, such as pan-tilt height, impeller rotation speed and depression angle, rotation range and cycle. PLC read and processed data and sent control command to frequency converters, electromagnetic valves and motors to achieve automatic adjustment of the above parameters. Meanwhile the data acquisition module collected data in real-time. The specific control method is as follows.

(1) Control of pan-tilt height The pan-tilt height measured by the displacement sensor was compared with set value in the PLC, and then adjusted through start or stop of oil pump motors or electromagnetic valves.

(2) Control of depression angle The depression angle measured by the tilt sensor was compared with set value in PLC, and then adjusted through the electric telescopic rod moving forward, backward or stop.

(3) Control of impeller rotation speed Output of the frequency converter 1 for wind machine motor was controlled by PLC. The motor speed was measured by encoder 1 and controlled via a closed loop.

(4) Control of pan-tilt The frequency converter 2 for pan-tilt motor was controlled by PLC and completed the corresponding control action. Meanwhile the current angle position of pan-tilt was measured by the rotation angle sensor and the feedback was sent to PLC for closed loop feedback control. The speed of pan-tilt motor was monitored by encoder 2.



Note: Motor 1 is for wind machine; Motor 2 is for pan-tilt.

Figure 3 Schematic of control system

4 Control system hardware design

The control system hardware was mainly composed of programmable controller, data acquisition module and sensors.

4.1 Sensors

The tilt sensor measuring the depression angle of the impeller and was installed on one side of the rotation shaft of supporting tube, which was connected to support stands in the pitch mechanism. The production of single shaft type LCA318 (Rion Technology) met the requirements (current output mode of 4-20 mA, very wide measurement range of –60°-+60°, resolution of 0.05°). Based on capacitive micro pendulum principle, the gravity on the pendulum produced corresponding capacitance change when the sensor inclined.

The displacement sensor WPS-L-1000-A1 was used to monitor the height (maximum pull speed 500 m/s, maximum measurement range 10 m). The displacement sensor was set on the pedestal, and the pull tab was hooked on the lower edge of the fixed platform perpendicular to the main part.

The encoder was placed inside the motor for the detection of motor speed. The type of encoder 1 and encoder 2 are E6B2-CWZ6C (Omron Corp.). The angle sensor coupled with the center shaft of auxiliary platform measured the position angle of the pan-tilt. It consisted of multipolar circular raster, photoelectric encoder, magnetic encoder, rotary and transformer[21,22]. Incremental encoder E6B2-CWZ6C (Omron Corp.) was selected.

4.2 Programmable logic controller

Based on the above distribution of I/O points, FX2N-48MR-001 (Mitsubishi Electric Co., Ltd.) was chosen with 16 input points, 16 output points, AC power supply, DC input and relay output.

The communication extension board FX-485-BD (Mitsubishi Electric Co., Ltd.) was added between PLC and data acquisition module DAM3055 (Beijing Art Technology Development Co., Ltd). The external wiring of PLC and distribution of I/O points are shown in Figure 4[23].

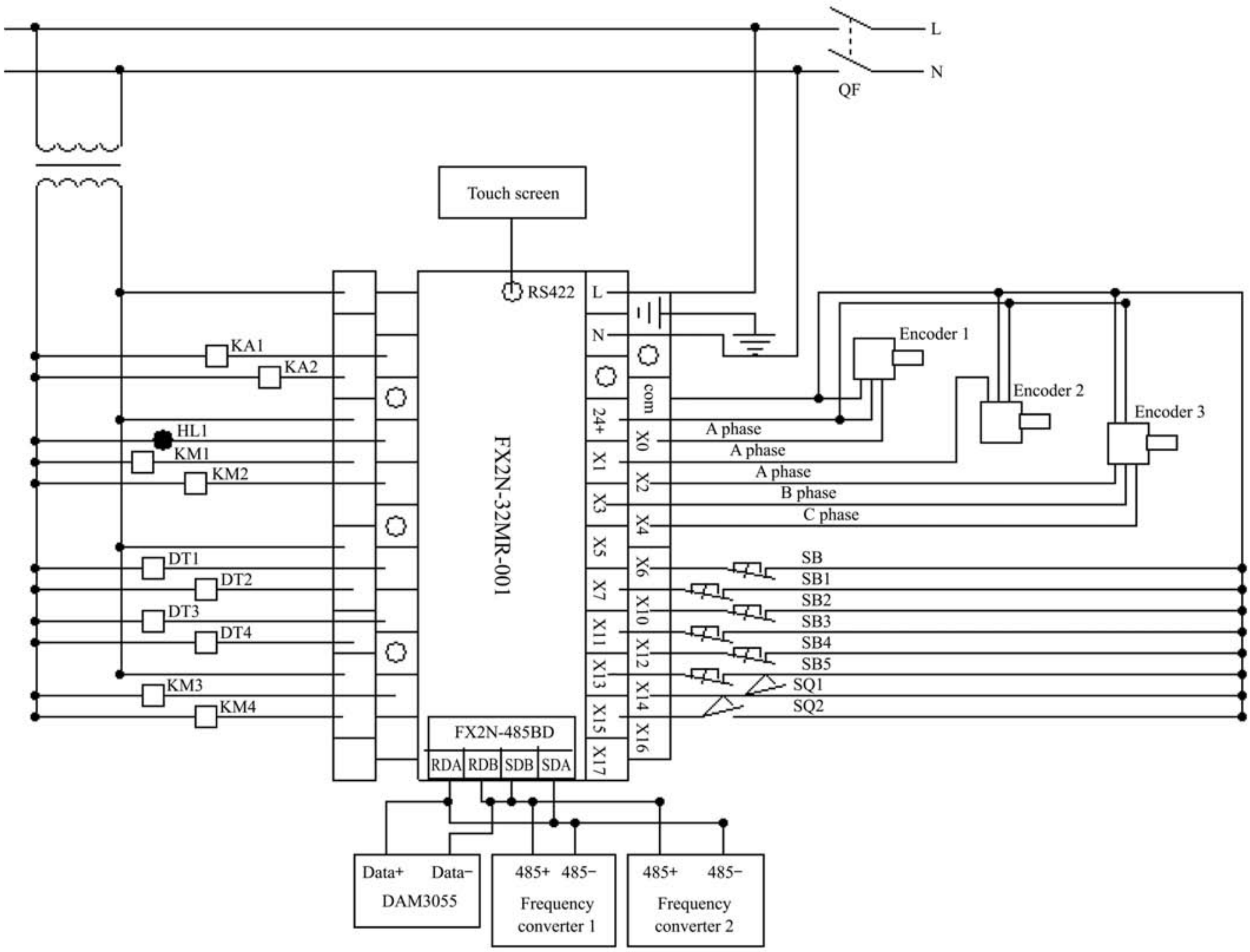


Figure 4 External wiring of PLC and I/O distribution

KA1 and KA2 were the intermediate relays used for forward and reverse control of electric telescopic rod; KM1 and KM2 were the relays for oil pump motor; DT1 and DT2 were electromagnetic valves; KM3 and KM4 were the relays for forward and reverse control of pan-tilt; SB was hydraulic platform stop button; SB1 and SB2 were manual button for lifting the hydraulic platform; SB3 was stop button; SB4 and SB5 were forward and reverse buttons; SQ1 and SQ2 were limit switches.

4.3 Data acquisition and communication modules

Multiple analog signals were collected including the signals from displacement sensor, angle sensor and weather sensors. Data acquisition module DAM3055 was used to convert the analog to digital signal and it collected up to 16 analog signals simultaneously. The module communicated with PLC via RS-485 port based on the protocol Modbus RTU.

Touch screen TK6102i (Weinview Co., Ltd.) was selected as human interface device to input parameters and display data.

5 Control system software development

The software was designed according to the process requirement of the system consisting mainly of the touch screen and the PLC control program.

5.1 Program design of touch screen

The touch screen completed multitasks of human-computer interaction, chart display, real-time data acquisition, real-time communication and data analysis. As shown in Figure 5, the touch screen program mainly consisted of the interfaces of system setting, operational parameters setting, manual and automatic operation, trend curve and system monitoring.

In the operational parameters setting interface hydraulic platform height, impeller rotation speed, depression angle, rotation range and cycle were set. PLC read and processed the above setting and then sent commands to actuators or frequency converters. The monitoring screen displayed operational parameters and failure/emergency alert.

5.2 Control program design of PLC

The PLC control program in ladder diagram language was written based on the software GX Developer, mainly including main program of automatic control, initialization program, data acquisition and processing subroutine, height subroutine, impeller rotation speed subroutine, depression angle subroutine, pan-tilt subroutine and alarm subroutine.

(1) Initialization program dealt with communication parameter setting, state accessing, reset, manual/ automatic option and zero-position adjustment of pan-tilt.

(2) Data acquisition subroutine read pulse signals of encoders via PLC and analog signals (displacement, angle, weather data) via DAM3055 via FX-485-BD. Data processing program completed data comparison and calculation of motor speed, hydraulic platform height, depression angle, angle position and speed of pan-tilt.

(3) Height subroutine controlled the platform height to reach the target value or keep within allowable error. The height measured by the displacement sensor was compared with the target value in PLC. If the measured value was higher or lower than the target value, control output was carried out to turn on or off the solenoid valves for moving the platform down or up.

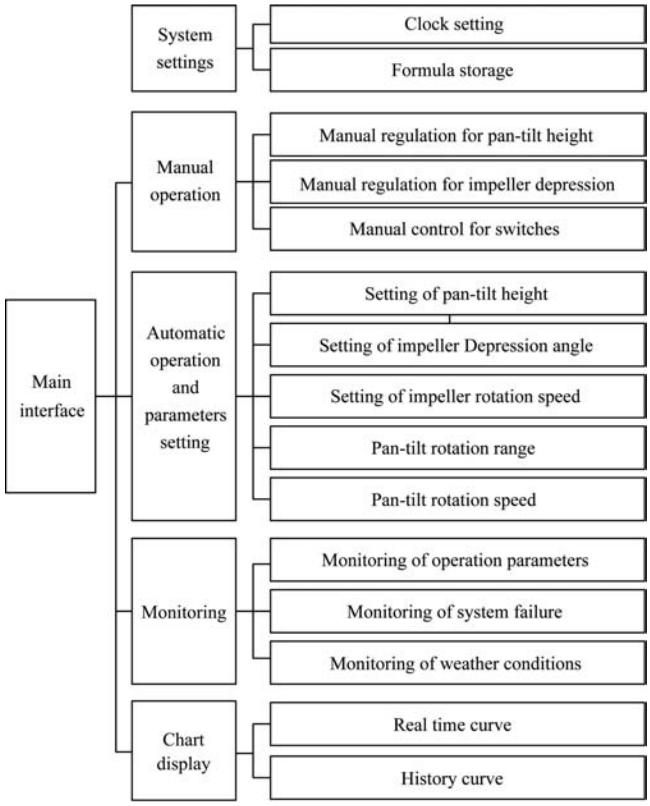


Figure 5 Program design of touch screen

(4) Depression angle subroutine: The depression angle measurement by LCA318 tilt sensor was compared with the targeted value. If it deviated from the target, PLC would send control command for reversing or forwarding the electric telescopic rod.

(5) Impeller rotation speed subroutine: The command of speed regulation was sent by PLC to frequency converter based on the set value through RS-485 port. The speed was calculated as follows,

$$N=60D_0\times10^3/(n\cdot t) \quad (1)$$

where, N was the impeller rotation speed, r/min; D_0 was count value; t was the counting time, millisecond; n was the encoder resolution,.

(6) Pan-tilt subroutine: According to the range of pan-tilt rotation entered on the touch screen, the right number of pulses needed for the angle encoder was calculated as follows,

$$P=\theta/_{\Delta\theta}=\theta/_{0.18}=5.56\theta \quad (2)$$

where, θ was the rotation range of pan-tilt. The reduction ratio between the geared motor and the slewing bearing was 1:4, and the reduction ratio of the geared motor was 1:473. Thus, the geared motor speed was calculated as follows,

$$4\times473\theta/(180T_m)=10.51\theta \tag{3}$$

where, θ and T_m were the range and pan-tilt rotation cycle, respectively.

The command was sent to frequency converter by PLC via FX-485-BD to run the pan-tilt at the set speed. Until the pulse number reached the calculated value P, the reversal command would be sent for inverse rotation, and the counter in PLC was cleared at the same time. The loop was repeated until the frequency converter received the stop command.

Due to the interference among operational parameters, the operation sequence was specified. The main working steps of automatic control are as follows.

Step 1: Input operational parameters after power-on, and checked whether the setting of pan-tilt height was valid. If so, called height subroutine to control the solenoid valves and then turned to Step 2; If not, the program turned to Step 2.

Step 2: Checked whether the setting of depression angle was valid. If so, called depression angle subroutine to control the electric telescopic rod and then turned to Step 3; if not, the program turned to Step 3.

Step 3: Checked whether the setting of the pan-tilt range or rotation cycle was valid. If so, called pan-tilt subroutine to control the rotation motor and then turned to Step 4; If not, the program turned to Step 4.

Step 4: Checked whether the setting of the impeller rotation speed was valid. If so, called pan-tilt subroutine to control the impeller motor and then turned to the next step. If not, the program turned to the next step.

If malfunctions occurred during the control, the above steps repeated until artificial maintenance. The main program flow of automatic control is shown in Figure 6.

5.3 Overshoot processing

When actual height and angle reached the set values during the control, the overshoot would appear because of the mechanical inertia. As the operational parameters' change slightly influenced frost protection effect, high precision control was not necessary. Because of low-speed lifting, the method of threshold reserved was adopted to control the height of the hydraulic platform for allowable error range. When the column up or down approach set value and within the allowable deviation range, stop it immediately.

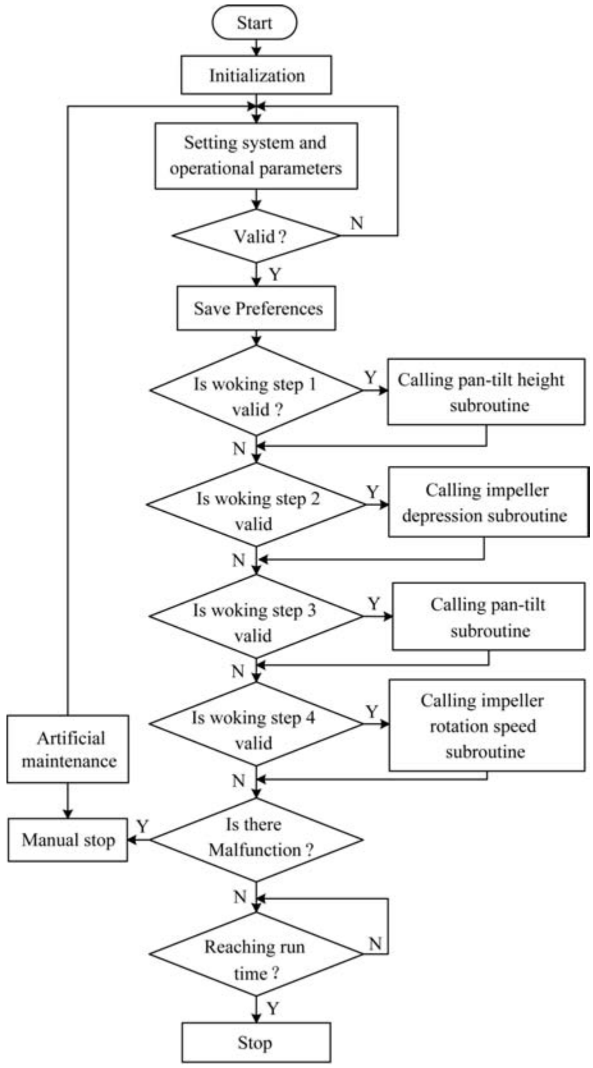


Figure 6 Main control program flowchart

As the pan-tilt rose or dropped at different speed, the height threshold was set separately. Because of mechanical inertia and the lag of data transmission, the threshold was obtained through repeated experiments. The control of depression angle and pan-tilt rotation range was similar to that of the pan-tilt height.

5.4 Data communication

While PLC collected pulse signal from encoders directly by the input terminals X0-X6, it communicated with DAM3055 and two frequency converters via RS-485 port. While the communication between PLC and frequency converters was for motor speed regulation, the one between PLC and DAM3055 was to complete real-time acquisition of dynamic analog signals from displacement sensor, angle sensor and meteorological sensors. Master-slave response mode was adopted for the communication with PLC as the master, and DAM3055, frequency converter 1 and frequency converter 2 as the slaves, with address assigned to 1, 2, 3 respectively.

6 Control system test

The operation of the control system includes parameter setting and information query.

When the system power was on, the parameters such as calendar and clock were set first. Then in the real-time data display interface current values of operational parameter and weather conditions were read, and the historical data trend charts were obtained. In the parameter setting interface target values of the operational parameters or threshold were set according to requirements, and then the "Set" button were pushed to make the setting take effect. Finally the target values of operational parameters were gradually to be achieved or remained within allowable error range.

The application of the system was carried out in a hilly tea filed. Because of the small size of tea plant and weak intensity of the thermal inversion the following parameters were set as the hydraulic platform height of 8 m, impeller rotation speed of 580 r/min, depression angle of 8°, pan-tilt rotation range of 90° and rotation cycle of 1 min. The operational procedure was as follows: (1) switching on the main circuit and control system, and in 20 s starting the touch screen; (2) reading current values of parameters in the data display interface; (3) Turning to the operational parameter setting interface and setting the target values, and then pushing the "Set" button; (4) pushing the "Start" button to run the control system.

The test results showed that the control accuracy of all the parameters was achieved with the average errors of 2.11 cm for height, 9.5 r/min for impeller rotation speed, 0.83° for pan-tilt rotation range and 0.061 min for rotation cycle.

7 Conclusions

A hydraulic lifting system was designed as performance test-bed for frost protection wind machines, and its control system was developed for evaluation and operational parameters' optimization of wind machines. The control of impeller rotation speed and depression angle, pan-tilt height, rotation range and rotation cycle was achieved through PLC, touch screen and sensors. PLC control and touch screen interfaces were programmed to realize the functions of data acquisition, operational parameters' monitoring and control. The control system achieved expected accuracy and was easy to operate for testing the performance of various frost protection wind machines.

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