DESIGN AND EXPERIMENTAL STUDY OF A SMART TREE WHITEWASH DEVICE BASED ON HUMAN–COMPUTER INTERACTION
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基于人机交互智能树干涂白装置的设计与实验研究

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ABSTRACT
Tree whitewash has the functions of parasite prevention and cold protection and is therefore commonly used in the maintenance and management of trees. At present, tree whitewash mainly relies on manual operation, which has the problems of low efficiency, poor quality, and uneven distribution of the whitewash agent. To address this issue, this study developed a smart tree whitewash device based on human–computer interaction. The device was controlled mainly by a programmable logic controller (PLC). Once the trunk information collected by sensors was received by the PLC, it would control the up and down motions of the ball screw to manipulate the mechanical arm for whitewash. In addition, a Mitsubishi GT12 touch screen was adopted to facilitate system operation. Subsequently, a whitewash experiment was performed on poplar trunks with lengths of 10–35 cm using three different whitewash devices, i.e., a backpack sprayer, a semi-automatic tree sprayer, and the proposed smart tree whitewash device; the efficiency and the amount of whitewash agents used were compared. The results suggested that as the tree diameter at breast height increased, the amount of required whitewash agent elevated accordingly. In this case, the time required by the backpack sprayer and the semiautomatic tree sprayer to complete the job both increased, whereas that required by the smart tree whitewash device remained almost identical. In terms of work efficiency, the time required by the smart whitewash device to whitewash a tree was 109.89 s, which was approximately 1/2 of the time required by the backpack sprayer or 2/3 of that required by the semiautomatic tree spraying device. Meanwhile, the amount of whitewash agent required by the smart whitewash device to whitewash a tree was 140.23 g, which was approximately 0.46 of the amount required by the backpack sprayer or 0.74 of that required by the semiautomatic tree spraying device. Therefore, it was concluded that the proposed smart tree whitewash device could not only improve the work efficiency of tree whitewash but also greatly reduce the amount of whitewash agent required, thereby decreasing the cost and minimising environmental pollution. This study provides theoretical guidance and technical support for future research on smart tree whitewash devices.

摘要
树木刷粉具有预防寄生虫和御寒的功能，因此常用于树木的养护和管理。目前，树木刷白主要依靠人工操作，存在效率低、质量差、刷白剂分布不均匀等问题。针对这一问题，本研究开发了一种基于人机交互的智能树干涂刷装置。该装置主要由可编程控制器(PLC)控制。PLC 接收到传感器采集到的主干信息后，通过控制滚珠丝杠的上下运动来操纵机械臂进行粉刷。并采用三菱 GT12 触摸屏，方便系统操作。随后，在 10-35 cm 的杨树树干上进行了刷白试验，试验采用 3 种不同的刷白装置，即背包式刷白机、半自动刷白机和本发明的智能刷白装置；比较了该方法的漂白效率和用量。结果表明，随着树径胸高的增加，所需的漂白剂用量也相应增加。在这种情况下，背包喷雾器和半自动树木喷雾器完成这项工作所需的时间都增加了，而智能树木粉刷设备所需的时间几乎相同。在工作效率方面，智能刷树装置刷树时间为 109.89 s，约为背包式喷雾器刷树时间的 1/2 或半自动喷雾器刷树时间的 2/3。同时，智能刷白装置刷白树木所需的刷白剂用量为 140.23 g，约为背包式喷雾器所需用量的 0.46，或半自动刷白装置所需用量的 0.74。因此，本文提出的智能树木涂刷装置不仅可以提高树木涂刷工作效率，而且可以大大减少所需的刷白剂用量，从而降低成本，减少环境污染。本研究为未来智能树干刷白设备的研究提供了理论指导和技术支持。

INTRODUCTION

Trees can easily freeze and crack in the early spring. This is especially the case for large trees with darker colours, thicker trunks, and weaker bark *(Liu, 2017)*. Trunk whitening can effectively mitigate such issues. The whitening agent can form an alkaline layer on the surface of the tree trunk to prevent the invasion of pathogens, kill the parasites and bacteria on the bark, accelerate the healing of tree wounds, and prevent animals from chewing on the bark *(Zhang, 2018)*.

The whitening equipment is mainly divided into three categories. The first type, a knapsack sprayer, is the most widely used *(He et al., 2016; Guo et al., 2019)*. This equipment mainly relies on manual spraying and it is difficult to control the range of the spray, which can cause low-quality spraying. Furthermore, when whitening trees with a small diameter at breast height (DBH), a large part of the whitening agent is lost into the air. The second category is a semi-automatic tree-spraying device. Although this type of device has special designs for the container, it requires manual operation and is susceptible to interference from the external environment. The third category includes more advanced whitening machines; however, most of them are in the theoretical-research stage and the production cost is relatively high *(Chen, 2018)*.

In response to the above problems, this paper proposes an intelligent tree-trunk whitening device, based on human–machine interaction, which uses ultrasonic sensors to measure the diameter of the tree trunk and transmits it to the programmable logic controller (PLC). The PLC controls a three-dimensional screw that drives the manipulator to spray the trunk and uses a Mitsubishi GT12 touch screen to achieve human–machine interaction. Such a design is user-friendly, versatile, and environmentally friendly. The performance of the proposed smart tree whitewash device was compared to that of a backpack sprayer and a semiautomatic tree spraying device. The results of this study can provide theoretical guidance and technical support for future research on smart tree whitewash devices.

MATERIALS AND METHODS

DESIGN PLAN

This design uses the Mitsubishi PLCFX2N-48MR programmable logic controller (hereinafter referred to as the PLC), an HC-SR04 ultrasonic ranging sensor, a human–machine interface, and other equipment to realize the electrical control of the whitening device. With a programmable controller as the core and an ultrasonic ranging sensor and human–machine interface as auxiliary tools, the design constitutes a manual/automatic electrical control system that integrates the collection and processing of live-wood DBH measurements and intelligently whitens the tree according to the different DBH *(Sun et al., 2018)*.

The PLC sends a pulse trigger signal to the ultrasonic distance-measuring sensor through the analogue/digital (A/D) conversion module of the PLC, and a high-level output is obtained at the receiving port. When the high-level output is received, a timer is started. When this port reaches a low level, we can read the timer value and calculate the measured time to obtain the DBH of the tree. The measurement result is fed back to the PLC, and the moving speed of the manipulator and the spraying amount of the discharge port are matched, according to the DBH of different trees *(Masood et al., 2020)*. The device is divided into two control modes: manual and automatic.

The whitening-agent tank has a built-in level gauge. When the whitening agent is insufficient or overfilled, the human–machine interface will remind the user to replenish or stop the paint supply, respectively. The system structure diagram is shown in Figure 1.

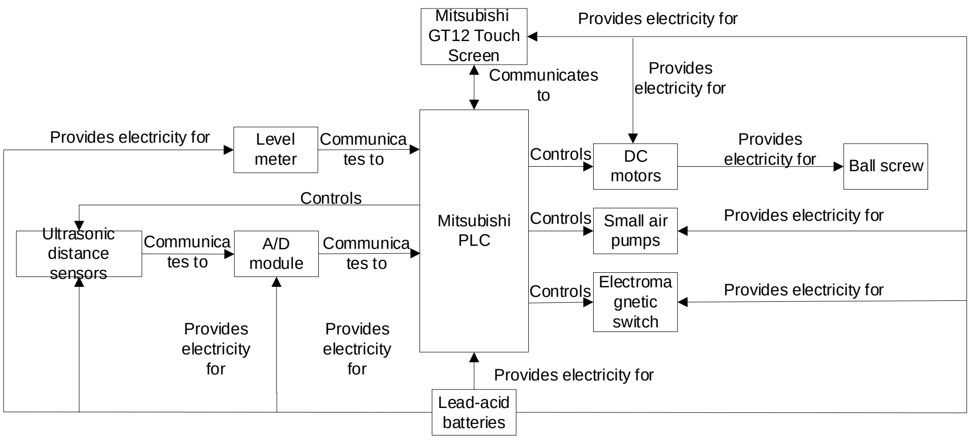

Fig. 1 - System Structure

HARDWARE DESIGN

Hardware

The mechanical part of this design is composed of a manipulator, a ball screw, a direct-current (DC) motor, an ultrasonic ranging sensor, a small air pump, a nozzle, an electromagnetic switch, a tank, a rubber tube, and a float-level gauge inside the whitening-agent charging barrel. It adopts two semi-circular clip structures, which are opened and closed by an electromagnetic switch. The manipulator is connected to the ball screw, and the DC motor controls the movement of the ball screw to spray up and down.

In this design, three ultrasonic distance-measuring sensors are installed, and placed at equal distances above the circular clamp. Three special nozzles are installed in the inner groove of the clip. The diameter of the liquid outlet is slightly larger than that of an ordinary water nozzle. Because lime water is more likely to block the output than water, the wide-mouth nozzle can be used for a better discharge. The sprayed liquid from each nozzle can cover a 120° range.

The whitening agent is pressurized from the tank by a small air pump, fully mixed, and then injected into the manipulator through a hose. The float-level gauge in the tank can sense the height of the solution in the tank and sends it to the human–machine interface. The interface can provide operators with information, such as whether to replenish the solution, whether the container has been filled, and the status of the battery. The mechanical-structure diagram is shown in Figure 2.

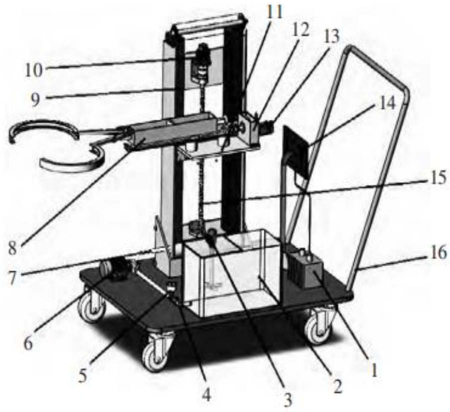

Fig. 2 - Mechanical Structure

1. Storage battery. 2. Tank. 3. Float-level meter. 4. Regulator. 5. Water meter. 6. Small air pump. 7. Hose. 8. Manipulator. 9. Lifting platform. 10. DC motor. 11. Cage. 12. Gearbox. 13. DC motor. 14. Human–machine interface. 15. Ball screw. 16. Cart.

Selecting Device Types

PLC

Compared to the PLCs of other companies, the PLC produced by Mitsubishi has the advantages of intuitive and easy-to-understand programming, detailed instructions, dedicated positioning instructions, and easy-to-control servo and stepping motors *(Li et al., 2015)*. Hence, this design uses the Mitsubishi PLC as the control. However, the PLC models produced by Mitsubishi Corporation are numerous, and each has its own characteristics. The FX2N-48MR model PLC was selected as the main controller *(Jiang et al., 2020)*, and its parameters are shown in Table 1.

Table 1

PLC FX2N-48MR Parameters

Name	Value
I/O Count	48
Output	Relay
Power	24 V DC
Rated Voltage	100–240 V AC
Rate Frequency	50 / 60 Hz

A/D module

The A/D module can convert the external analogue signal into a digital signal. This design mainly uses the Mitsubishi PLC, so the A/D module uses the FX0N-3A module *(Tang et al., 2021)*. This module has two analogue-signal input channels and one analogue-signal output channel. The input/output signals can be either voltage or current. The main performance parameters are shown in Table 2.

Table 2

FX0N-3A Main Characteristics

A/D Conversion	Input Voltage	Input Current
Analogue input range	0–10 V DC	4–30 mA DC
Effective digital output	8-digit binary	
Conversion time	100 ms	
D/A conversion	Output Voltage	Output Current
Analogue output range	0–10 V DC	4–30 mA DC
Effective digital input	8-digit binary	

Ultrasonic distance-measuring sensor

Compared with several types of ultrasonic ranging sensors on the market, the sensor performance of the HC-SR04 is better *(Gunawan et al., 2019)*, the control is simple, and the price is low. Specific performance parameters are shown in Table 3.

Table 3

HC-SR04 Performance Parameter Table

Characteristic	Value
Operating Voltage	5 V
Ultra-small quiescent working current	< 5 mA
Accuracy	0.3 cm
Blind spot	< 2 cm

Human–machine interface

The human–machine interface of the Mitsubishi GT12 series has a flexible and scalable configuration. It can be connected with the Mitsubishi-series PLC for data communication and control, and the operation is simple. Its specific performance parameters are shown in Table 4.

Table 4

Human–Machine Interface GT12(640×480) Parameters

Characteristic	Value
Screen Size	12.1 inch
Resolution	640×480
Input Voltage	DC 24 V (+25%, -20%)
Power	< 11 W
Current	< 29 A (10 ms)(max)
Temperature	-20 °C–60 °C

Float–level gauge

The float-level gauge has a simple structure, is convenient to debug, and can be widely used in high-pressure and viscous media. It fits in perfectly with the working environment of our device. Its specific performance parameters are shown in Table 5.

Table 5

Float-Ball Level-Gauge Performance Parameters

Characteristic	Value
Range	0–3500 mm
Supply voltage	12–36 V DC
Precision	±2.5% F.S.
Nominal pressure	≤ 2.5 MPa
Temperature	-20–120 °C

I/O distribution and PLC peripheral wiring diagram

I/O distribution

The I/O distribution of the selected device includes 14 inputs and six outputs. The final I/O allocation table is shown in Table 6.

Table 6

I/O Distribution

Input			
Number	**Module**	**Location**	**Function**
1	SB1	X000	Power off
2	SB2	X001	Power on
3	SB3	X002	Raise mechanical arm
4	SB4	X003	Lower small mechanical arm
5	SB5	X004	Lower medium mechanical arm
6	SB6	X005	Lower large mechanical arm
7	SB7	X006	Initiate spraying
8	SB8	X007	Stop spraying
9	SQ1	X010	Upper limit switch
10	SQ4	X011	Lower limit switch
11	s	X012	Virtual Switch (Small Trees)
12	m	X013	Virtual Switch (Medium Trees)
13	l	X014	Virtual Switch (Large Trees)
14	FR	X015	Overload protection
Output			
Number	Module	Location	Function
1	KM1	Y0000	Raise mechanical arm
2	KM2	Y0011	Lower mechanical arm
3	KM3	Y002	Run pump
4	L1	Y003	Mechanical rising indicator
5	L2	Y004	Mechanical lowering indicator
6	L3	Y005	Pump-running indicator

PLC peripheral wiring diagram

According to the I/O allocation table combined with the selected hardware, the peripheral wiring diagram of the PLC is shown in Figure 3.

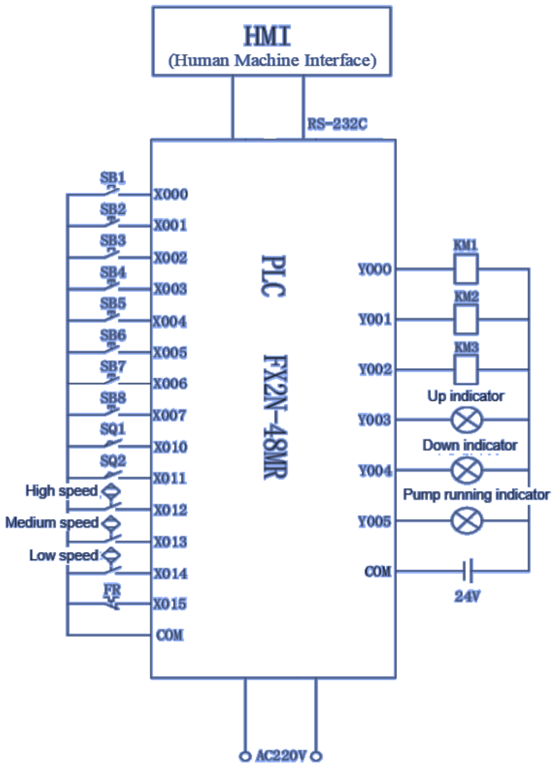

Fig. 3 - Peripheral wiring diagram

SOFTWARE DESIGN

Working principle

The data measured by the HC-SR04 ultrasonic distance-measuring sensor are transmitted to the PLC through the A/D module, and the PLC executes the program to control the DC motor to drive the three-dimensional screw movement. It thereby controls the raising and lowering movements of the manipulator and the opening and closing of the spray valve.

In view of the differences of tree diameters at breast height, to achieve better adaptability and a higher use efficiency of the whitening agent, the automatic mode control has three different spraying modes for small, medium, and large trees *(Teimouri et al., 2020)*. (See Table 7 for the parameters.) The operating can use manual mode to select different speeds, start or stop spraying, and other operations, according to their needs.

Table 7

Three Spraying Modes and their Parameters

Mode	DBH/cm	Manipulator Movement Speed/(cm/s)	Output Pressure/MPa
Small Trees	DBH < 15	8	0.15
Medium Trees	15 ≤ DBH < 30	6	0.20
Large Trees	30 ≤ DBH	4	0.25

Work process

The workflow of this design is divided into three parts, as shown in Figure 4.

Preparation stage: The PLC controls the manipulator to encircle the tree trunk, measure its DBH, and select the appropriate spraying operation mode.

Spraying stage: The PLC controls the DC motor and valve switch to whiten and spray the trunk.

Ending stage: After the spraying operation is completed, the PLC recycling manipulator completes the whitening operation of the entire tree trunk.

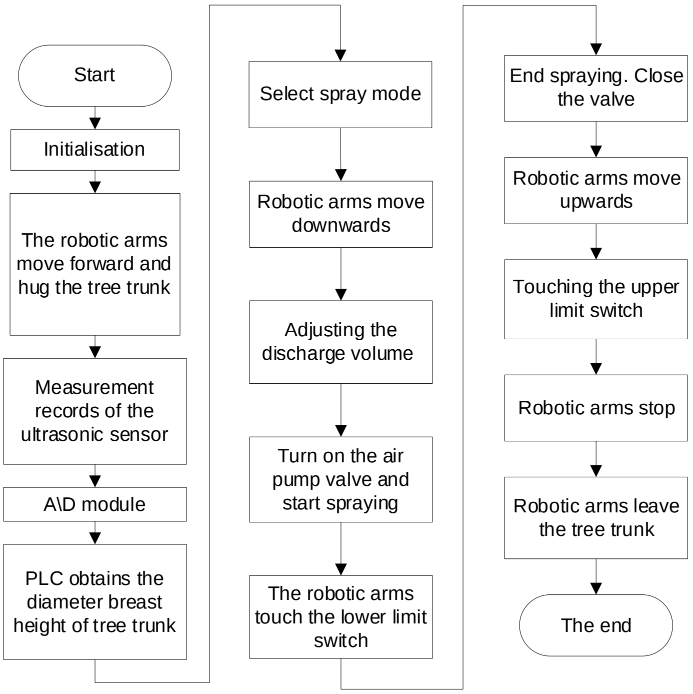

Fig. 4 - Work Process

Simulation software

Human–machine interface

To facilitate the staff's work, manual and automatic operation modes are set on the human–machine interface for trees with different DBH. The automatic mode is divided into three modes. After measuring the distance with the ultrasonic distance-measuring sensor installed on the ring clamp of the manipulator, the PLC calculates and selects the corresponding mode for spraying, so that trees of different DBH can be evenly covered with the whitening agent. The manual mode allows the operator to select operations, such as start spraying, stop feeding, and select speed, according to their needs. The human–machine interaction interface is shown in Figure 5.

Manual control mode

The operator starts by pressing the main start switch. When s/he presses the manipulator start button, the manipulator starts to move up, and the indicator light turns on. The upwards movement stops after it touches the travel switch. If the user presses the start button of the feed, the spray indicator light turns on. By pressing the down button, the staff can choose the corresponding speed, according to the tree's conditions. For example, if the manual control mode is selected, the DBH < 15, the downward-movement indicator light turns on, and the DBH is displayed as 11 cm, and the speed is displayed as 8 cm/s, and the Liquid is displayed as 46L. The manipulator simultaneously moves down to complete the spraying work. When the manipulator reaches the bottom end and touches the travel switch, the movement and spraying stop. The human–machine interface is shown in Figure 6.

Automatic Control Mode

The ultrasonic distance-measuring sensor measures the breast diameter of the tree and feeds the data back to the PLC. After the PLC has finished the calculation, a mode is automatically selected for whitening. The manipulator starts to work at the top end. The material is discharged, while the manipulator moves down the tree. When it reaches the bottom end and touches the travel switch, the spraying and moving stop. The user should raise the manipulator to the highest position again to prepare for the next whitening. For example, if the automatic control mode is selected, the 30 > DBH > 15, the downward-movement indicator light turns on, and the DBH is displayed as 27 cm, and the speed is displayed as 6 cm/s, and the Liquid is displayed as 45L. The manipulator simultaneously moves down to complete the spraying work. When the manipulator reaches the bottom end and touches the travel switch, the movement and spraying stop. The human–machine interface is shown in Figure 7.

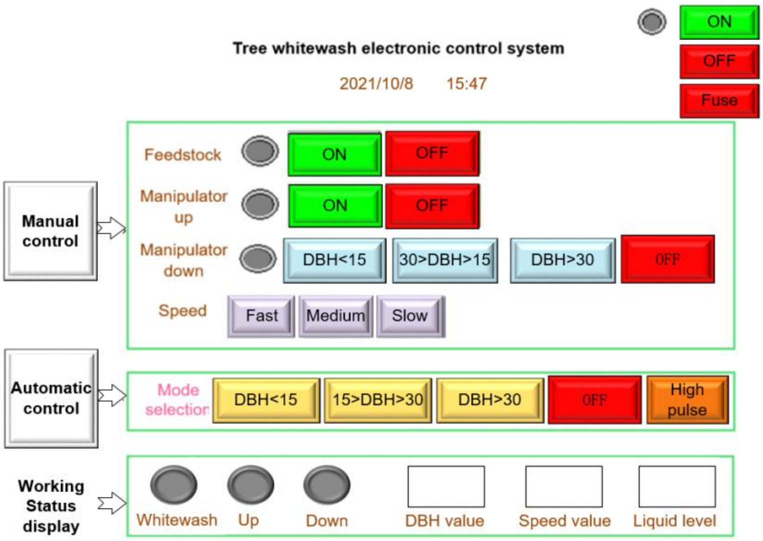

Fig. 5 - Human–machine interface

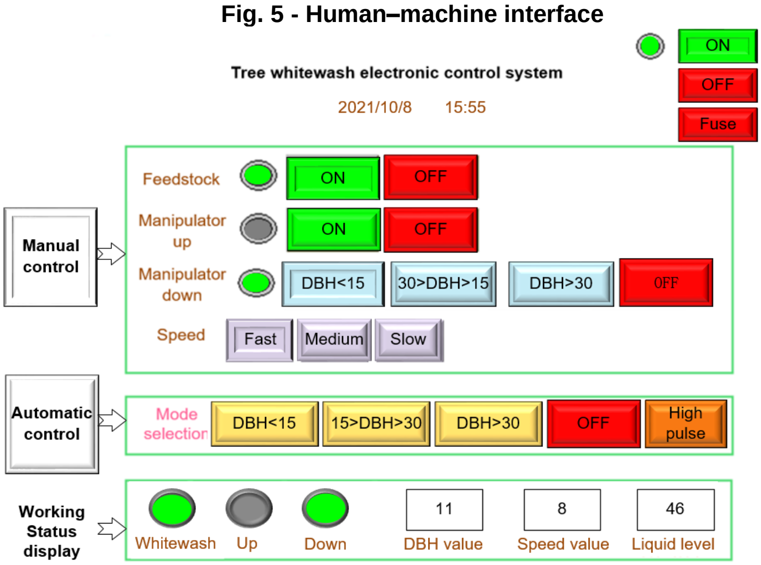

Fig. 6 - Manual control. Human–machine interaction interface simulation diagram

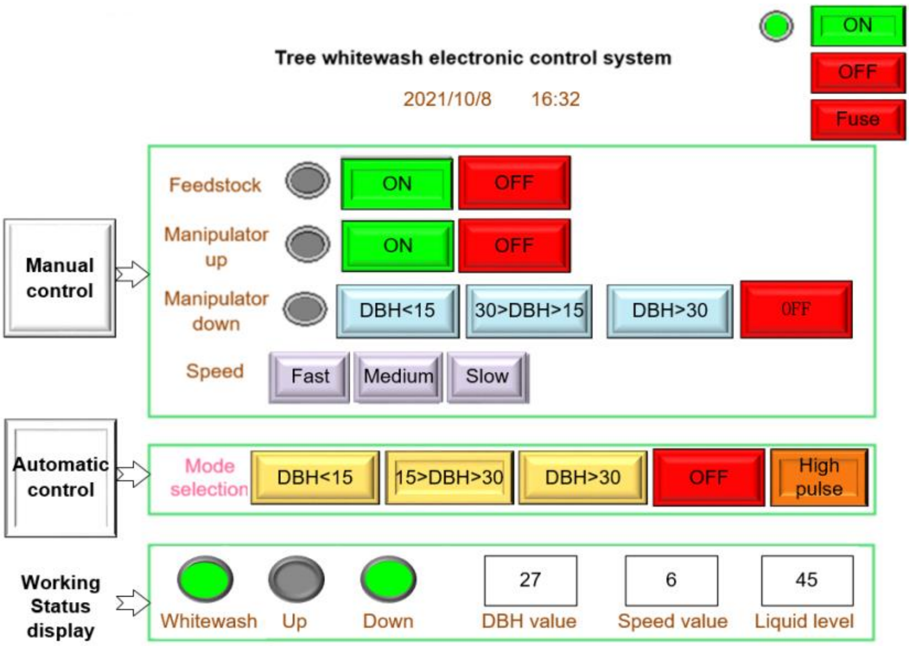

Fig. 7 - Automatic control. Human–machine interaction interface simulation diagram

RESULTS AND ANALYSIS

On October 8, 2021, 36 poplar trees with a diameter of 10–35 cm at breast height were selected on the Hohhot campus of the Inner Mongolia Agricultural University. The selected samples were divided into three groups, each consisting of trees with similar diameters at breast height. Subsequently, the trunks of these poplar trees were whitewashed with a backpack sprayer, a semiautomatic spraying device, and the proposed smart tree whitewash device to a height of 1.4 m from the ground. The Senle® tree whitewash agent was used after being diluted with water at a ratio of 1: 3. Finally, the operation time and the amount of the whitewash agent required by the different devices to complete the job were recorded, as shown in Table 8 and Figure 8.

Table 8

Comparison results of different tree whitewash devices

Tree diameter at breast height	Backpack sprayer		Semi-automatic tree spraying device		Smart tree whitewash device	
	Operation time	Amount of whitening agent	Operation time	Amount of whitening agent	Operation time	Amount of whitening agent
[cm]	[s]	[g]	[s]	[g]	[s]	[g]
10	165.23	203.57	140.85	92.01	94.14	89.11
11	166.25	212.11	145.86	105.14	94.35	89.98
14	173.35	230.98	151.98	119.08	100.58	101.25
18	177.01	236.65	156.11	126.01	98.35	112.25
21	178.20	255.85	157.58	135.32	105.36	121.01
23	188.56	461.57	159.40	143.52	111.10	123.23
24	189.44	380.52	161.12	157.67	96.35	123.89
27	190.38	386.11	166.18	173.35	99.63	134.21
29	200.25	392.22	167.87	183.25	101.25	138.24
31	204.38	303.24	172.14	188.50	109.89	140.23
33	207.91	412.4	178.38	193.87	108.32	148.32
35	214.35	418.47	181.26	206.35	99.98	156.21
Average	187.94	324.47	161.56	152.01	101.61	123.16

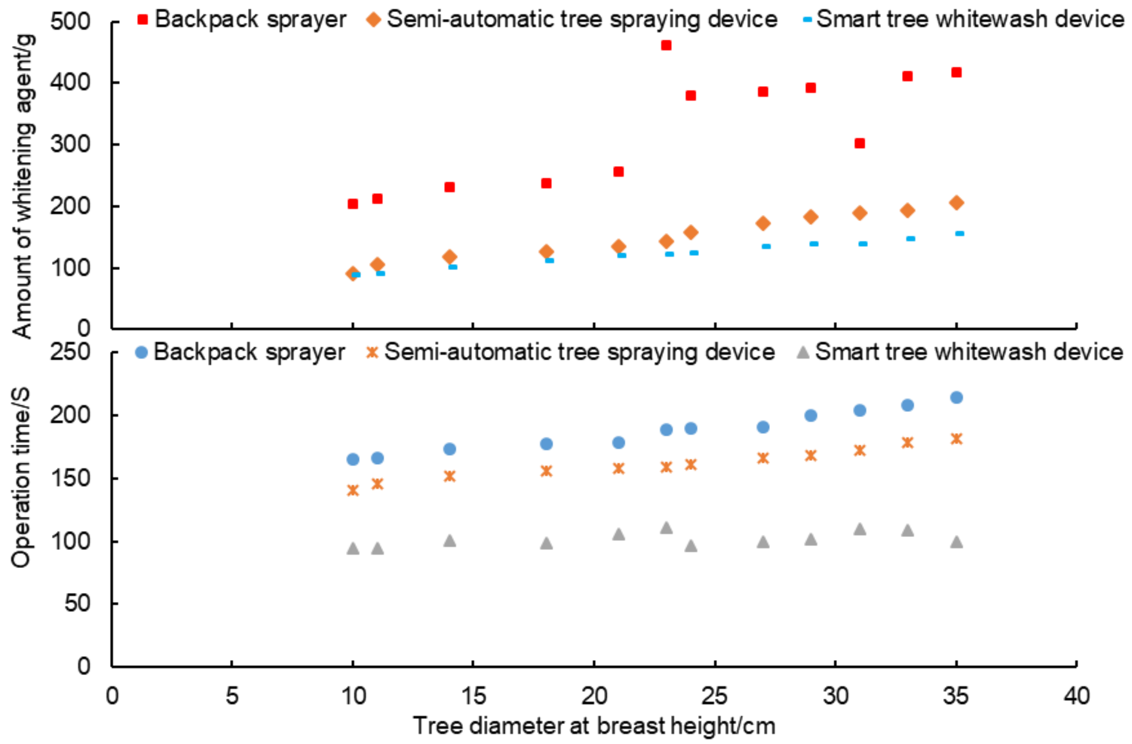

Fig. 8 - Analysis of test results of different white coating machines

Table 8 and Figure 8 shows that as the tree diameter at breast height increased, the amount of whitewash agent required increased accordingly. Additionally, the time required by the backpack sprayer and the semiautomatic tree sprayer to complete the job both increased, whereas that required by the smart tree whitewash device remained almost identical. In terms of work efficiency, the time required by the smart whitewash device to whitewash a tree was 109.89 s, which was approximately 1/2 of the time required by the backpack sprayer or 2/3 of that required by the semiautomatic tree spraying device. Meanwhile, the amount of whitewash agent required by the smart whitewash device to whitewash a tree was 140.23 g, which was approximately 0.46 of the amount required by the backpack sprayer or 0.74 of that required by the semiautomatic tree spraying device. Therefore, it was concluded that the proposed smart tree whitewash device could not only improve the work efficiency of tree whitewash but also considerably reduce the amount of required whitewash agent, thereby decreasing the cost and minimising environmental pollution.

CONCLUSIONS

Hardware and software parts comprise the two major elements of the intelligent trunk-whitening device, based on human–machine interaction, and the working principle was analysed. This design used the PLC as the control core and an ultrasonic distance sensor to measure the diameter of the trees at breast height. The device then matched the corresponding whitening speed and output, which effectively solved the problems of uneven whitening and the waste of whitening agent. Based on the PLC and combined with a human–machine interface, the operation was simpler, the spraying was more uniform, and the quality and efficiency of trunk whitening were effectively improved.

A comparison of the proposed device with two other commercially available tree whitewash devices indicated that the time required by the smart whitewash device to whitewash a tree was 109.89 s, which was approximately 1/2 of the time required by a backpack sprayer or 2/3 of that required by a semiautomatic tree spraying device. Moreover, the amount of whitewash agent required by the smart whitewash device to whitewash a tree was 140.23 g, which was approximately 0.46 of the amount required by the backpack sprayer or 0.74 of that required by the semiautomatic tree spraying device.

The smart tree whitewash device developed in this study has the advantages of a uniform spraying effect, short operation time, and an even distribution of the whitewash agent, thereby effectively improving both the quality and the efficiency of tree whitewash.

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