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Vertical Smart Greenhouse Planting System

Chiung-Hsing Chen, Yi-Chen Wu,* and Jin-Wei Xu

Department of Telecommunication Engineering, National Kaohsiung University of Science and Technology, 142, Haishuan Rd., Nanzih District, Kaohsiung City 811, Taiwan

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In this study, we take the cultivation of orchids as an example. We aim to design an organically grown and intelligent greenhouse system to help farmers reduce labor costs and improve efficiency by combining technology and agriculture in severe planting environments or workforce shortages. The architecture of this system includes an intelligent greenhouse, machine vision, and wireless transmission. With vertical agriculture as the main body of the greenhouse, embedded systems adjust the greenhouse environment and establish a human–machine interface. Users can alter the environment according to different crops and their own needs. Vertical farming is a method of growing crops vertically on top of each other. Through the shelf structure of vertical agriculture, a customized track is established. A mobile camera is mounted on the track and combined with machine vision technology to design an instant pest detection system. When pests are found in agricultural products during their growth, organic pest control products are used to eliminate them.

1. Introduction

Agriculture is an essential industry in Taiwan, with agricultural exports accounting for approximately 57.2%, making it one of Taiwan's leading export industries.(1) Taiwan is located between tropics and subtropics, with a warm climate and abundant rainfall, which is suitable for the growth of crops. Owing to its narrow terrain, Taiwan is not conducive to large-scale agricultural cultivation. However, with reliance on exquisite agricultural products with high added value, such as flowers and fruits, the export value of farm products has increased yearly. Flowers are one of Taiwan's essential agricultural products that are exported. In 2017, agrarian policies shifted to improving the quality of flowers and the management effectiveness of flower farmers. The scale of the domestic flower industry is expanding yearly. In 2019, the export value of flowers reached 6.6 billion yuan. Among them, the export value of orchids accounts for more than 80% of the total export value of flowers, with phalaenopsis accounting for the most significant amount at 4.6 billion yuan.(2) Owing to its geographical location, Taiwan is affected by an average of 3 to 5 typhoons yearly, which cause high economic losses to Taiwan's agriculture.(3) In addition to the impact of natural disasters, agriculture also faces the problem of

*Corresponding author: e-mail: 72325@nkust.edu.tw
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an aging workforce. The work content is also relatively complex because the average salary of traditional agricultural farmers could be lower. This situation makes young people reluctant to engage in agriculture-related jobs.

To solve the problems faced by agriculture, modern agriculture has begun to integrate with science and technology to reduce labor costs, improve the quality and yield of agricultural products, and achieve sustainable development. There are many successful cases worldwide where technology is integrated with agriculture. Examples are the precision automation and standardized greenhouse system technology developed in the Netherlands and the root drip irrigation technology in Israel. The purpose of this study is to create an intelligent greenhouse planting system and use vertical shelf-type planting as the main structure of the greenhouse. The rack structure in vertical agriculture is used to build tracks and carry cameras to inspect crops for insect damage. In this study, we introduce innovative solutions by integrating vertical farming, machine vision, and pest detection systems with organic farming techniques. The embedded system with real-time wireless transmission distinguishes this research from existing approaches in smart agriculture.

2. Materials and Methods

In this study, we take the innovative greenhouse as the central axis. This greenhouse system includes functions such as environmental regulation and pest identification. The system uses the embedded system National Instruments (NI) myRIO (reconfigurable I/O) to adjust the environment and uses cameras to capture crop images and send them back to the host. The image is processed through the NI vision development module (NI Vision) to identify whether pests have occurred in crops. Figure 1 is a schematic diagram of the system architecture. This architecture uses ball screw slides to establish a track so that the camera can move on the shelves to observe whether there is any insect damage.

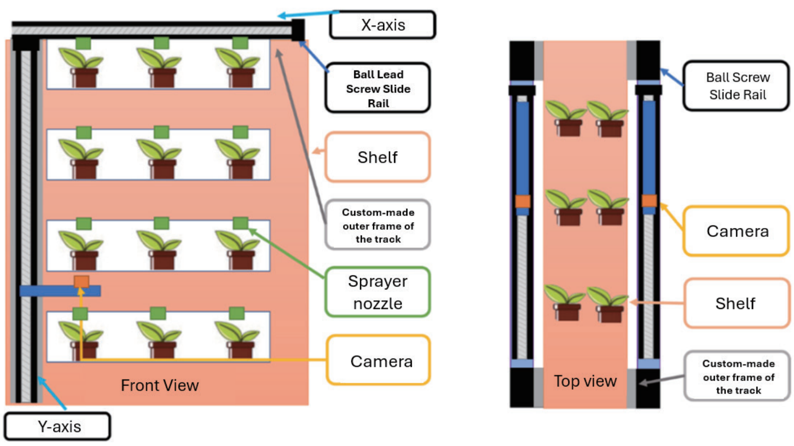


Fig. 1. (Color online) Schematic diagram of this system architecture.

2.1 NI myRIO embedded system

In this study, we need to control multiple motors and environmental conditioning equipment, and the motors need to run in parallel to achieve the highest efficiency operation mode. The embedded system NI myRIO can achieve synchronous execution and has the advantages of high performance and real-time control, which can reduce the overall system operation error rate.[(4)] It can load LabVIEW programs internally to achieve independent operation. It uses the Linux operating system internally, making its operating system more stable. It has the advantages of FPGA and is an embedded system architecture developed to improve system performance. It combines the benefits of processors (enabling complex system applications) and FPGAs (synchronicity design and high-speed input and output configurations). Input and output signals are planned, and the front end is processed through FPGA. Then, the data is handed over to the processor for subsequent operations and applications. Figure 2 shows the NI myRIO architecture diagram.

2.2 Intelligent vertical greenhouse system

The advantage of a greenhouse farm is that local environmental conditions can be modified according to the needs of the plants.[(5)] It helps farmers produce different types of crops while extending the growing season. It can also effectively use pesticides, fertilizers, water, and labor to improve harvest quality and yield. The innovative vertical greenhouse used in this study combines the advantages of different precision agricultural greenhouses. This greenhouse features centralized management, environmental regulation, wireless sensor networks, and intelligent agricultural work.[(6–9)] As shown in Fig. 3, this greenhouse system is based on an embedded system and uses environmental sensors to measure data about the greenhouse's environment (such as temperature, light, and humidity). The embedded system controls the greenhouse environment on the basis of the returned greenhouse environment parameters, such as turning on ceramic heating lamps, turning on fans, and spraying water mist. Greenhouse environmental data and pest identification results will be wirelessly transmitted to the host for

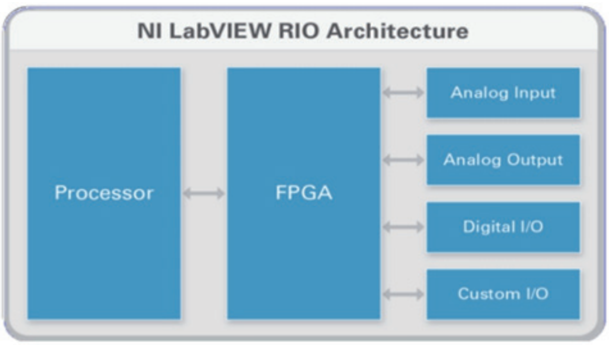


Fig. 2. (Color online) NI myRIO architecture diagram

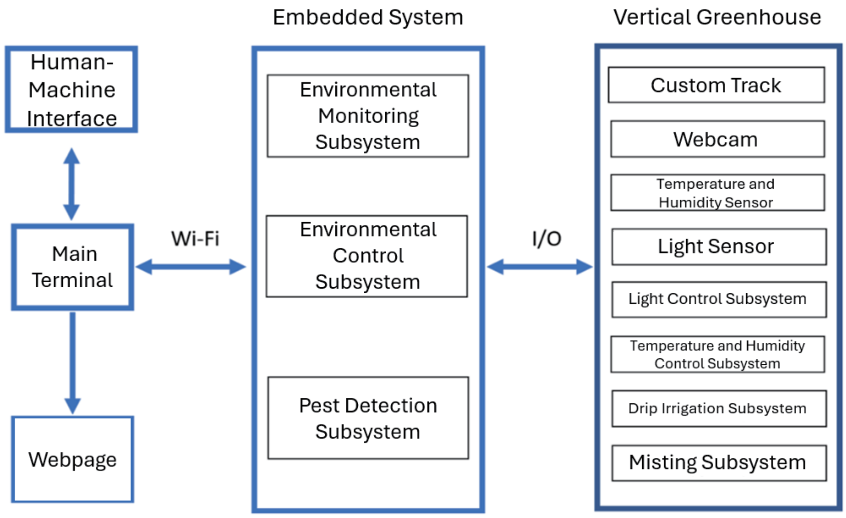


Fig. 3. (Color online) Intelligent vertical greenhouse system architecture.

storage through the built-in Wi-Fi module of the embedded system NI myRIO, allowing users to view the current status of the greenhouse in real time.

Figure 4(a) is a physical diagram of the customized track proposed in this paper. This track is mainly used to monitor the growth of orchids in real time with a slide rail and a camera. The customized track is composed of a ball screw slide rail and a synchronous belt linear slide table. The *Y*-axis (height) of the track can be adjusted to move the camera; the *X*-axis can be moved left and right to photograph the growth of each orchid, as shown in Fig. 4(b).

Since the *X*-axis needs to drive the *Y*-axis to move left and right, we use a ball screw slide rail with high tolerance to realize the *X*-axis, whereas for smaller loads, a synchronous belt linear slide is used to learn the *Y*-axis.[10]

2.2.1 Waterway system

Two waterway systems were used in this study: the drip irrigation and water mist subsystems. The drip irrigation subsystem irrigates crops regularly, whereas the water mist subsystem is used to increase humidity. When pests are detected, the system automatically switches to the spraying mode with organic pesticides. This process is controlled by a solenoid valve, as shown in Fig. 5. The drip irrigation subsystem uses a submersible motor to send water from the water tank to the drip irrigation head on the crop breeding basin for regular irrigation, as shown in Fig. 6. The water mist subsystem has two working states: spraying water and organic insecticides. The system contains two solenoid valves corresponding to the water tank and the organic insecticide, as shown in Fig. 7.

(a) (b)

Fig. 4. (Color online) (a) Customized track physical diagram and (b) camera platform.

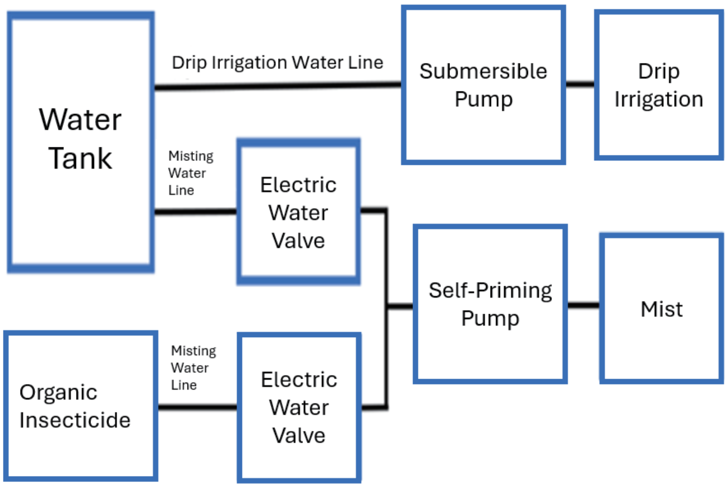
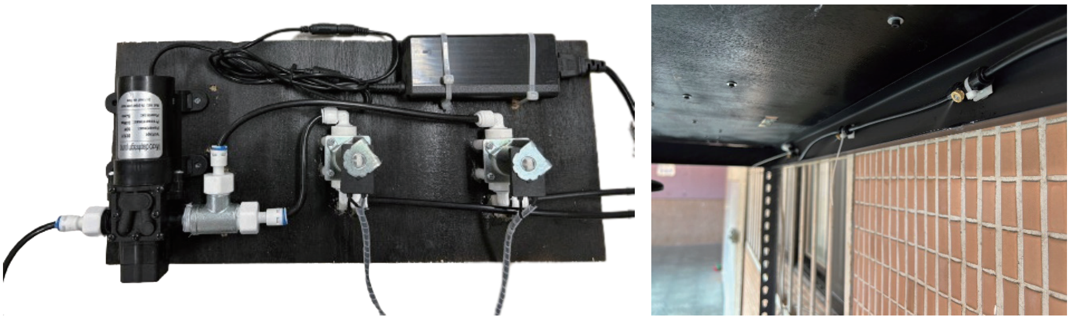


Fig. 5. (Color online) Waterway system architecture diagram.

Fig. 6. (Color online) Drip irrigation subsystem in action.



(a) (b)

Fig. 7. (Color online) (a) Water mist subsystem control panel and (b) water mist subsystem in action.

2.2.2 Environmental monitoring and control subsystem

We used temperature, humidity, and light sensors to collect temperature, humidity, and light intensity data in the greenhouse, respectively.[11,12] Through the built-in Wi-Fi module of NI myRIO, the collected data are sent to the host, and the data are averaged and stored in the MySQL database. In addition, these data will also be displayed on the human–machine interface and web pages. The averaging algorithm in this (SMA: Simple Moving Average) is used to reduce outliers in collected data.[13] This system uses 1000 data per second to perform the SMA algorithm. This method can effectively reduce the abnormal noise of the data. The mathematical formula of *SMA* is shown in Eq. (1): n is the total number of data and k_i is the ith piece of data in the total data.

$$SMA = \frac{1}{n}\sum_{i=1}^{n} k_i \tag{1}$$

It can be seen from Fig. 8 that the red line in the figure represents direct data access and the white line represents the data processed by the SMA algorithm. When the data are directly accessed, the numerical fluctuations are very abnormal and do not conform to the temperature changes in everyday environments. After being processed by the SMA algorithm, the data changes are minimal and consistent with the actual temperature changes.

We designed an environmental control subsystem to control each planting shelf's light, temperature, and humidity in the vertical agriculture system. The system provides control signals to the light control subsystem and temperature through the data fed back by the environmental monitoring subsystem.[14] Since we used a vertical greenhouse, the construction method prevented sunlight from reaching the crops evenly, causing problems such as uneven illumination. Therefore, we chose the timing control method for design. Users can use the light intensity recorded by the environmental monitoring subsystem and the actual growth status of crops. We adjusted the system's turn-on time and allocated corresponding light tubes to improve the growth quality of crops. As shown in Fig. 9, the environmental control subsystem provides fuzzy and proportional-integral-derivative (PID) control for users to choose. As shown in Fig. 10, the environmental control subsystem can adjust the temperature and humidity in the

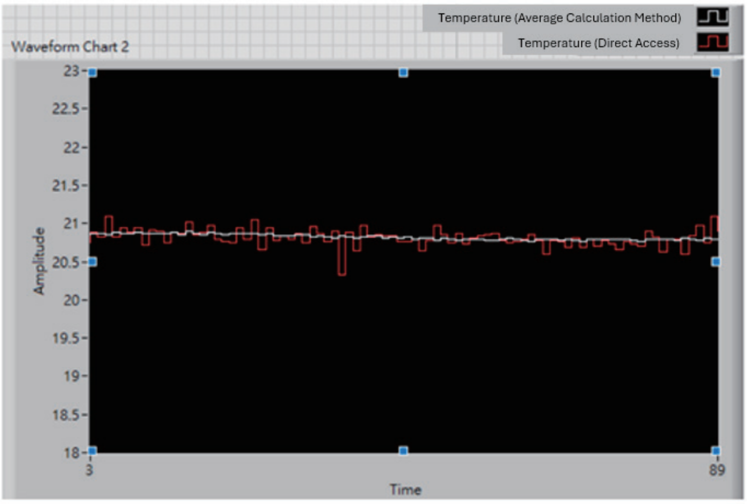


Fig. 8. (Color online) Comparison chart of temperature data before and after the SMA algorithm.

Fig. 9. (Color online) Practical application diagram of plant growth lights.

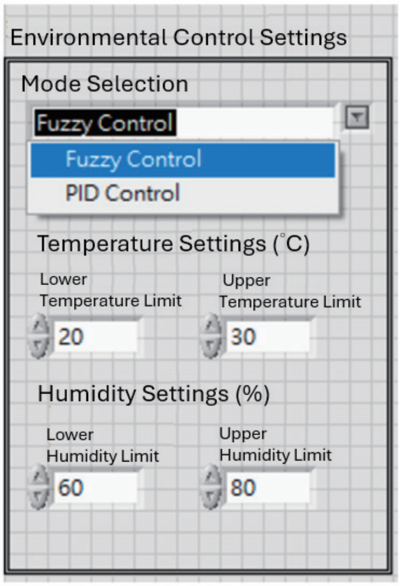


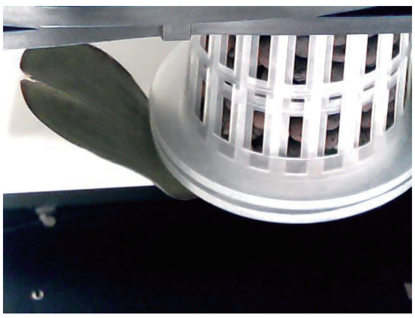
Fig. 10. (Color online) Environmental control setting human–machine interface.

greenhouse on the basis of the data fed back by the environmental monitoring subsystem. The temperature and humidity control subsystem makes the environment in the greenhouse suitable for growing crops, thereby increasing the growth rate and yield of plants.[15]

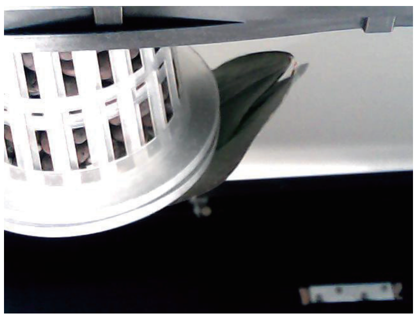
2.2.3 Pest detection subsystem

The pest detection subsystem in this study uses a customized track with a camera and is developed using NI Vision. Users can set related settings, such as the subsystem's startup time and shooting interval, through the human–machine interface. After the system is started, the customized track will move the camera to shoot under different orchids. The shooting sequence is shown in Fig. 11, starting from A.1 and ending at F.2. Because the underside of leaves is usually wetter, darker, and less exposed to the wind than the surface, these factors make the underside of leaves an ideal growing environment for insects.(16) To solve the problem of insect damage on the underside of leaves, we used cameras to shoot the right and left undersides of the plants from bottom to top, as shown in Fig. 12. Through this shooting method, insect pests on the back of leaves can be detected early, and treatment measures can be taken to prevent them from multiplying and damaging the plants.

Fig. 11. (Color online) Schematic diagram of customized track movement sequence.



(a)



(b)

Fig. 12. (Color online) (a) Image below the right leaf and (b) image of the underside of the left leaf.

3. Experimental Results and Analysis

To verify the feasibility of the intelligent vertical greenhouse planting system designed in this study, we conducted experiments under a desired temperature of 25 ℃ and a humidity of 70% RH.

3.1 Temperature and humidity environment control

Figure 13 shows the temperature of the fuzzy control result chart, and the expected temperature is 25 ℃. When the system becomes stable, the maximum error is approximately 0.1 ℃. Figure 14 shows the temperature PID control result chart; the predicted temperature is 25 ℃. When the system reaches stability, the maximum error is approximately 0.1 ℃. Figure 15 shows the results of humidity fuzzy control. The expected humidity is 70% RH. When the system reaches stability, the maximum error is about 3% RH. Figure 16 shows the moisture PID control result chart. The expected humidity is 70% RH. When the system reaches stability, the maximum error is about 2.5% RH.

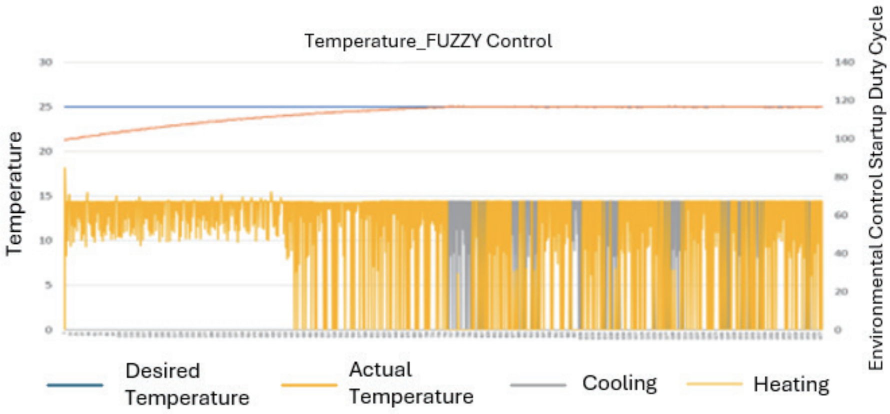


Fig. 13. (Color online) Temperature fuzzy control result graph.

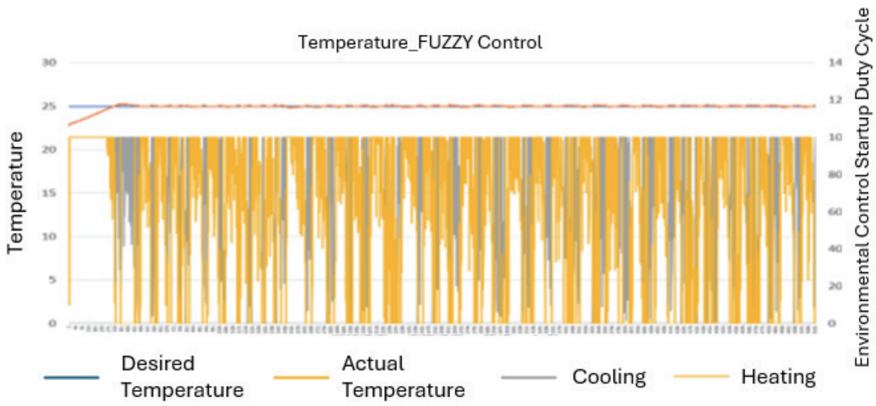


Fig. 14. (Color online) Temperature PID control result graph.

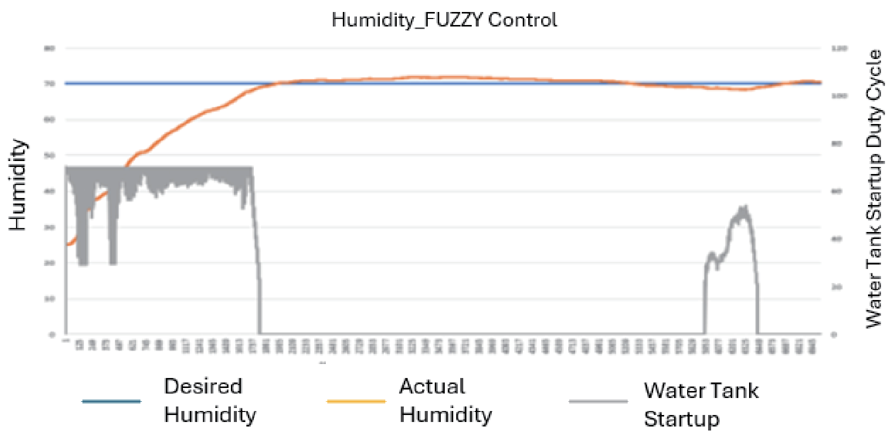


Fig. 15. (Color online) Humidity fuzzy control result chart.

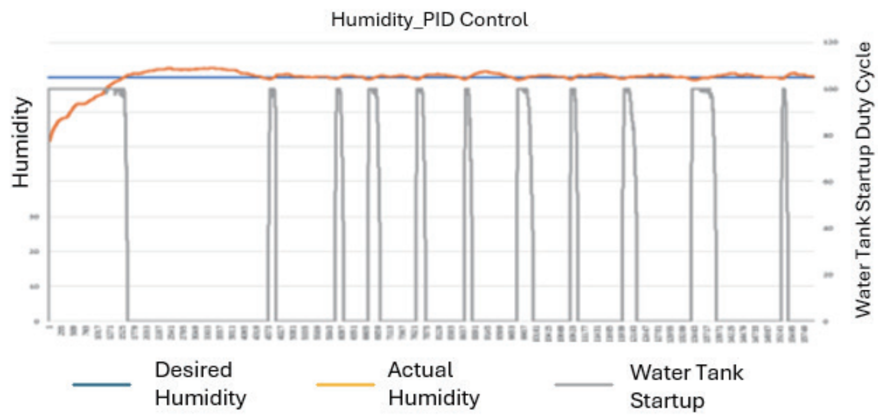


Fig. 16. (Color online) Humidity PID control result graph.

3.2 Pest detection

When a pest is detected during the operation of the pest detection subsystem, the human–machine interface will light up to remind the user, as shown in Fig. 17. Then, the relevant pictures are saved in the designated folder for users to view. At the same time, the system will activate the water mist subsystem to spray organic pesticides to achieve the effect of pest control.

3.3 Discussion of results

According to the results, the system was tested under controlled conditions with a set temperature of 25 ℃ and a target humidity of 70% RH. The PID control showed a maximum temperature error of ±0.1 ℃, whereas the fuzzy control exhibited a higher initial oscillation with a maximum error of ±0.15 ℃. In humidity control, the PID control stabilized at a 2.5% RH error margin, whereas the fuzzy control had a 3% RH margin with noticeable oscillations during

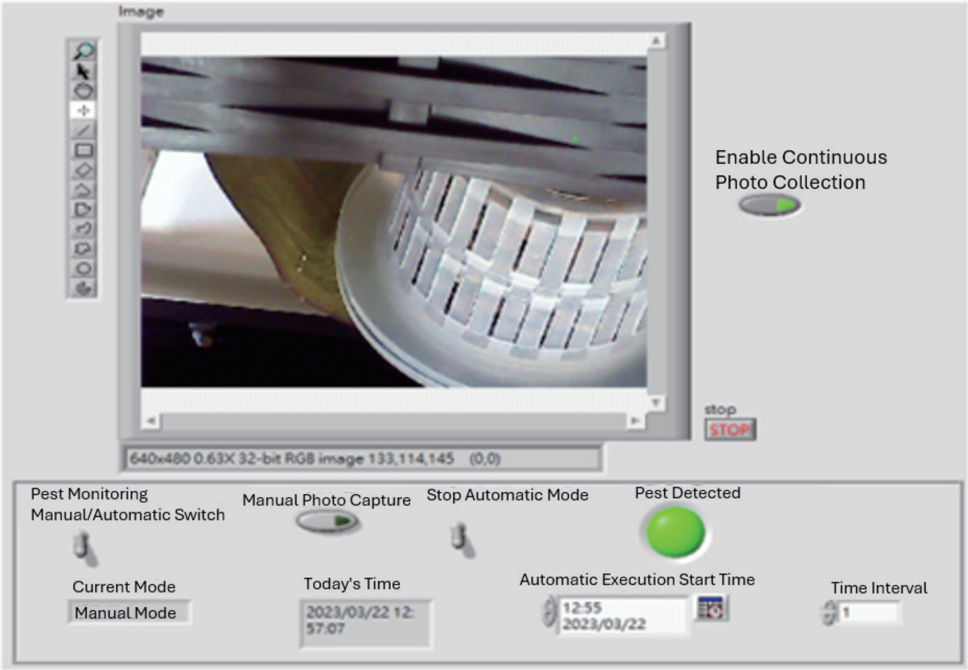


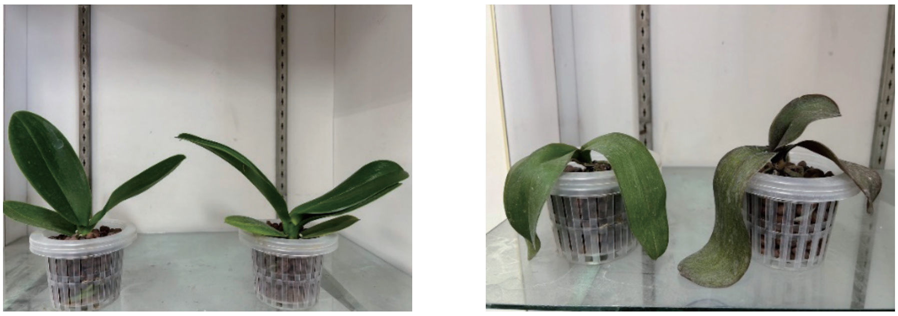
Fig. 17. (Color online) Pest detection subsystem.

startup. The overall effect is within a reasonable error range, whether it is fuzzy or PID control. However, the performance comparison between PID and fuzzy control reveals that PID outperforms fuzzy control in humidity regulation, with less oscillation and better stability. Fuzzy control shows more oscillation at startup, particularly in humidity control. The pest detection subsystem can effectively detect the occurrence of pests through NI Vision and effectively prevent damage caused by pests through thurible biocontrol agents. According to the comparison between Figs. 18(a) and 18(b), it can be observed that the leaves of orchids cared for using the system are more colorful, and the root system is more robust. On the other hand, the leaves of orchids grown naturally in indoor environments appear drooping and dim in color. It can be seen that climate has an absolute impact on orchids.

In comparison with existing smart agriculture systems, our system demonstrates superior performance in temperature control and pest detection accuracy. Traditional systems often rely on manual intervention or less accurate sensors, whereas our system, using PID and fuzzy control, achieves better stability in temperature regulation with minimal human input. Furthermore, integrating machine vision into pest detection allows for the precise early identification of pest distribution locations. This can also reduce crop losses more effectively than manual or semi-automatic systems.

4. Future Outlook

In recent years, automated equipment has gradually been introduced into agriculture, forming an emerging form called precision agriculture. Automating the agricultural production



(a) (b)

Fig. 18. (Color online) (a) Orchids without using system care and (b) orchids cared for using the system.

process aims to reduce labor costs, improve the quality of farm products, and reduce resource waste. Our institute's intelligent vertical greenhouse planting system can perform environmental monitoring and pest detection according to users' needs, effectively reducing crop losses and increasing farmers' profits. Although this research has achieved specific results, there is room for further improvement in the manufacturing process and overall precision.

Therefore, it is recommended that a professional processing manufacturer make the mechanism part to improve the precision and stability of the mechanism, thereby improving the operational efficiency and strength of the overall system. The ceramic heating lamp used in this study uses local radiant heat with a low heating speed and a limited heating range. It is recommended that future research considers using central air conditioning or implementing a temperature control system with hot and cold air ducts to increase the heating range and speed and further improve system efficiency and stability. Further integration of AI and improvements in the system's mechanical precision could enhance the system's efficiency. Future developments could explore adding deep learning for predictive analysis, improving crop yield and quality.

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