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Design and Test of Aerial Variable Spray Monitoring System

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Abstract:

To ensure that the spray volume per unit area does not change after the flight speed changes during the aerial spray process, and to achieve real-time monitoring of the spray, this paper develops a monitoring algorithm that can regulate the spray volume according to the flight speed change. Based on the algorithm and hardware circuit design, a set of aerial variable spray monitoring system is designed. Based on multi-information fusion technology, the system realizes real-time monitoring of information such as flight track, flight speed, spray volume and liquid residue, which can automatically adjust the spray volume according to the flight speed change. The test results indicate that the average error in flight track monitoring is 0.49m; the average error in flight speed monitoring is 4.67%; the average error in spray volume monitoring is 2.91%; the average error in liquid level monitoring is 1.78%; and the average error in variable control is 4.04%. The variable pesticide spray monitoring system studied in this paper can provide reference for the development of precision pesticide spray technology in agricultural aviation.

***Keywords**: Aerial spray, UAV, Spray volume control, Real-time monitoring, Variable spray.*

I. INTRODUCTION

On average, nearly 470 million hectares of crops in China are damaged by diseases and insect pests, causing nearly 225 million tons of food losses, accounting for about 20% of the total output, and causing more than 117.5 billion tons of economic crop losses[1]. At present, the main method for agricultural plant protection is mechanized spraying of pesticide, which the pesticide utilization rate is only 30%, due to the diverse topography of the planting areas in China, thus seriously reducing the pest control effect[2]. UAV aerial spray has the advantages of high operating efficiency and strong ability to respond to sudden disasters, which is widely used in agricultural plant protection[3]. Due to their easy take-off and landing, hovering capability, flexible operation, etc. unmanned aerial vehicles are widely used in hilly, mountainous, sloped and other complex terrains where large machines are difficult to operate[4-5]. UAV spray technology can improve China's agricultural mechanization level, which means great significance for achieving precision agriculture and sustainable development[6-7].

Regarding future development direction of precision agriculture, precision spray technology is a prerequisite for achieving precision agriculture. Precision spray requires precise monitoring of the spray process[8-12]. At present, UAV spray is mainly operated by visual remote control, and the spray volume cannot be changed during the spray process. The method cannot guarantee operation safety or spray quality, which easily leads to problems such as waste of pesticides, personal injuries, and crop damage. To this end, international scholars have studied monitoring of UAV spray[13-16]. The spray monitoring systems based on single-chip microcomputer designed by Zhai Changyuan[17], Lu Zhangtao[18] and Sun Qi[19] can simultaneously monitor the spray speed, spray pressure and spray volume. However, none of the above designs has track monitoring function, while track monitoring is particularly important for precise spray. Wingman GX manufactured by Adapco[20], Yuan Yumin[21] developed the UAV high-precision positioning system, and Zhang Zhen[22] developed the UAV monitoring system can monitor the UAV position and track, but monitoring of the spray condition is impossible. The UAV variable spraying ground monitoring system developed by Xing Hang[23] can manually control the spray volume. Such manually adjustment of spray volume based on experience can barely ensure spray accuracy[24]. The manned helicopter variable spray monitoring system designed by Zhang Ruirui[25]. Can automatically monitor the spray volume, but it targets at manned helicopters. Therefore, there are few research results in the monitoring system for UAV automatic variable spray operations.

To achieve whole-process automatic monitoring of UAV spray, automatically adjust the spray volume and avoid non-uniformity of spray, in this paper, based on full digestion and absorption of the international aerial variable spray technology, a set of aerial variable spray monitoring system suitable for China's national conditions has been developed. The system can realize real-time monitoring and display of information such as UAV flight track, flight speed, spray volume, and liquid residue, and can automatically adjust the spray volume according to the flight speed changes.

II. MONITORING SYSTEM DESIGN

2.1 Hardware Design

The hardware part mainly includes single-chip microcomputer, GPS, flow sensor, liquid level sensor, GSM wireless communication module, power regulator, button, display screen, etc., as shown in Fig. 1[26]. In this paper, the GPS system produced by Ublox is used to acquire UAV coordinates; the turbine flow sensor produced by Shandong Isentrol Electronic Technology Co., Ltd. is used to collect the spray volume; the capacitive liquid level sensor customized by Ganzhou Precision Metal Parts Factory is used to collect the liquid level of the pesticide box; the STM32F103VET6 single-chip microcomputer produced by British ARM is used as the microcontroller for fusion processing of multiple signals to determine the actual UAV flight status and spray status; the motor power regulator produced by Shenzhen Youxin Electronic Technology Co., Ltd. is used to adjust the spray volume; the TFT color screen and mobile terminal APP are used to intuitively display the spray status in the form of values and graphs.

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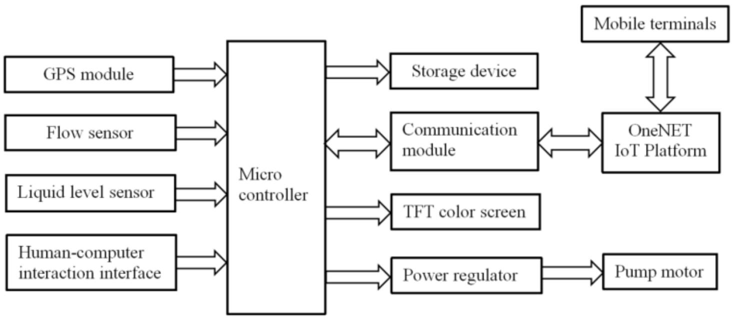
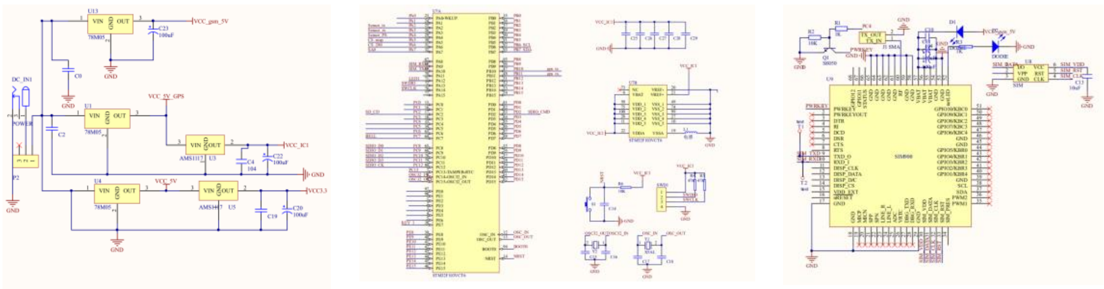


Fig 1: system frame diagram

In order not to affect the UAV normal operation, the system is equipped with an independent power module, which supplies power to the system through 8000mAh high-capacity lithium battery. Since the battery output voltage is 3.7V, and the single-chip microcomputer, sensors, communication module, etc. Require different voltages, in this paper, voltage regulator 78M05 is used to provide a stable 5V voltage for GPS, GSM communication modules and single-chip microcomputer, etc. The voltage regulator AMS1117 is used to provide stable 3.3V voltage for sensors, single-chip microcomputer and storage device. The circuit schematic diagram of the key system part is shown in Fig. 2. GPS and sensors exchange data with the single-chip microcomputer through serial communication mode, and the GSM communication module is connected to the single-chip microcomputer through TX and RX of the asynchronous serial communication port. Through the combination of the reset circuit, the crystal oscillator circuit and the internal circuit of the single-chip microcomputer, the single-chip microcomputer can operate stably.



a. The power supply circuit　　b. Single-chip microcomputer　　c. Communication module circuit

Fig 2: circuit diagram of key components

2.2 Software Design

The UAV spray monitoring system needs to meet the requirements of high monitoring accuracy, strong system stability, real-time data transmission and maintainability[27]. This design uses C language to compile software program through Keil compiler, the system software design flow is shown in Fig. 3. After the system is started, the initialization procedure is performed first, and then the GPS subroutine, the flight speed algorithm, the liquid level monitoring subroutine, the spray volume monitoring subroutine, and the spray volume control algorithm are sequentially called and executed.

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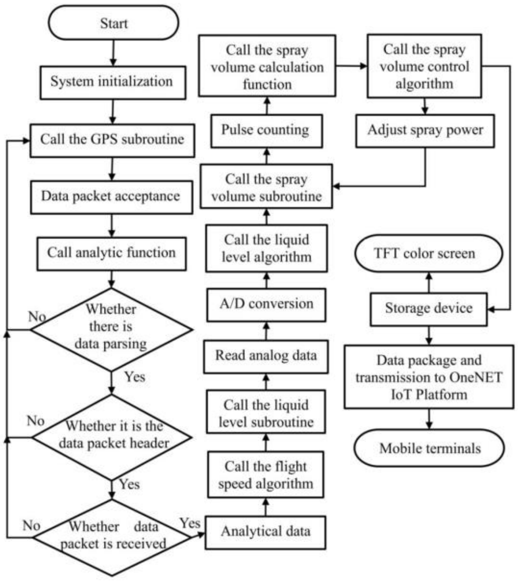

Fig 3: system software design flow chart

Since the GPS data structure adopts standard NMEA-0183 protocol, in GPS monitoring spray process, queue is usually used to receive data. The serial port will store the received data in the queue, and analyze the data in the loop program to acquire UAV coordinate information, so that flight track information can be obtained by connecting the coordinates of each time point. By calling the flight speed algorithm, the change of coordinate points per unit time is calculated to obtain the flight speed.

In this paper, dual sensors are used to monitor the liquid residue, that is, the initial height of the liquid level is collected by the liquid level sensor when the UAV is in a steady state or has not taken off. When the UAV has not taken off or is hovering, the liquid level algorithm converts the liquid level height analog information obtained by the liquid level sensor into digital information through the A/D converter, and then the liquid volume can be calculated based on cross section of the pesticide box. In the flight course, the discharged pesticide liquid is monitored by the flow sensor, and the residual pesticide volume can be calculated by subtracting the discharged pesticide liquid from the initial pesticide liquid.

Since the analog signal output by the flow sensor is a pulse signal, it is impossible to directly derive the spray volume. Therefore, the pulse signal needs to be first converted into a digital signal to obtain the digital frequency of the pulse. Then by calling the spray volume calculation function, the actual spray volume can be obtained and the function is shown in formula (1).

$$Q = \frac{f}{K} \times V \tag{1}$$

Where, Q —spray volume, mL/s; f —pulse frequency, Hz; K —the number of pulses output per revolution; V —the pesticide liquid volume per revolution, m L.

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The spray volume control is to change the duty cycle of the PWM signal, changing the average voltage across the liquid pump motor, thereby changing the speed of the liquid pump motor to achieve spray volume control. During the spray process, because the height of the same crop does not differ much, the flight height during spray remains unchanged. Therefore, the parameters that affect the spray area only include flight speed, spray width and spray time. When the flight speed, spray width or spray time increase, the spray area will increase. From which the spray area calculation formula can be derived as shown in equation (2).

$$S = vBt \tag{2}$$

Where, S —spray area, m2; v —flight speed, m/s; B —spray width, m; t —spray time, s.

It can be seen from equation (2) that the aflight speed, spray width or spray time are directly proportional to the spray area.

Since the spray beam has fixed length, the spray width remains unchanged. Therefore, the higher the flight speed is, the larger the spray area is. In order to ensure the spray effect and avoid uneven spray, the spray volume should vary with the flight speed. During normal spray operations, the UAV flight speed is between 3~6m/s, and the output power of the liquid pump varies between 60%~100%. Therefore, a functional relationship between flight speed and power can be established, as shown in equation (3).

$$P' = P_0\left(\frac{2}{15}v + 0.2\right) \tag{3}$$

Where, P' —spray power, W; P_0 —rated power of liquid pump, W.

The microcontroller reads sensors information once every 100ms, stores it in the data memory after calculation, and refreshes the information displayed on the TFT color screen. At the same time, the data is also packaged and sent to the OneNET IoT platform. The OneNet platform can be associated with multiple mobile smart devices at the same time. Through terminal devices connected to the platform network, remote real-time monitoring can be achieved [28]. For data transmission and uploading, this design adopts TCP communication protocol. The device is connected to OneNET through TCP connection for data interaction, which uploads the custom script to realize data transmission between the device and the cloud.

III. MATERIALS AND METHODS

The flight speed, flight track and spray volume are all important indicators in spray effect evaluation, and monitoring of the liquid residue can improve the spray volume control accuracy. To check the accuracy of the self-developed monitoring system in monitoring of flight track, flight speed, spray volume and liquid level and its precision in spray volume control, this paper performs flight track monitoring test, flight speed monitoring test, spray volume monitoring test, liquid level monitoring test and variable control test.

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3.1 Test Materials

The test site is a farmland of about 0.5hm2, the test time is June 19, 2020, the temperature is 21℃~29℃, and the wind speed is first-level wind(the speed is 0.3-1.5m/s, the direction is 90°). In the experiment, "Flying Spider" model quad-rotor electric UAV produced by Linyi Fengyun Aviation Technology Co., Ltd. is used as a carrier to be loaded with the monitoring device for the spray test. The liquid pump is rain dew model UAV liquid pump produced by Shandong Huisi Electronic Technology Co., Ltd., and the nozzle is the ST110-02 model nozzle produced by LECHLER, Germany.

3.2 Test Design

3.2.1 Flight Track Monitoring Test

Flight track monitoring is to monitor the latitude and longitude of the UAV flight track.

Test method: Before the test, arrange latitude and longitude of flight route on the test site through the Ovital map. During the test, the UAV was flown strictly according to the planned flight route. Conduct the test when there is no wind to avoid inaccurate positioning caused by wind speed. During the test, the monitoring system will monitor the flight track in real time, and compare the monitored track with the planned route to calculate the track error, thereby checking the accuracy of the monitoring system for track monitoring. The test was repeated 3 times, and the track monitoring operation site is shown in Fig. 4.

Fig 4: flight operation diagram

In this paper, the Gauss-Kruger equal-angle projection method is taken to convert the latitude and longitude information acquired by GPS into plane rectangular coordinate information [29-30]. In this paper, the Euclidean metric is used to calculate the true distance between two waypoints in three-dimensional space, that is, the track error. The calculation method is shown in equation (4).

$$\rho = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \tag{4}$$

Where, x_1—abscissa of planning point, m; x_2—abscissa of monitoring point, m; y_1—ordinate of planning point, m; y_2—ordinate of monitoring point, m; z_1—height of planning point, m; z_2—height of

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monitoring point, m; ρ —track error.

The track deviation mainly affects the accuracy of the spray area, which in turn affects the spray amount per unit area. When the deviation between the actual hectare application rate and the set spray rate per hectare is within 10%, it can be considered to meet the requirements of aerial spray operations [28]. That is, in the track monitoring test, when the spraying flow rate remains unchanged and the operating area varies between 90% and 110%, the track monitoring accuracy can be considered to meet the needs of aviation spraying. The average value of the track deviation can be used as the effective value to calculate the spray operations error per unit area by formula (5).

$$\phi = \left[\frac{(B \pm \delta)vt}{Bvt} - 1 \right] \times 100\% \tag{5}$$

Where, ϕ —Spray area error, %; B —spray width, m; t —operating time, h; v —operating speed, km/h.

3.2.2 Flight speed monitoring test

The test consists of five groups of three-level tests, that is, three-level tests are performed against flight speeds of 2m/s, 3m/s, 4m/s, 5m/s and 6m/s respectively. During the test, keep uniform linear motion of the UAV on a 100m runway and record the time of each flight. The system will automatically monitor the flight speed during the test. The ratio of 100m range to the flight time is the actual flight speed. By comparing the monitored flight speed with the actual flight speed through formula (6), the flight speed monitoring error can be obtained.

$$\delta = \left| \frac{v't'}{100} - 1 \right| \times 100\% \tag{6}$$

Where, δ —flight speed monitoring error; v' —flight speed monitoring value, m/s; t' —flight time monitoring value, s.

3.2.3 Spray volume monitoring test

The test consists of five groups of three-level tests, that is, three-level tests are performed against 60%, 70%, 80%, 90% and 100% power, and the average value is viewed as the actual value. This paper changes the liquid pump power through the regulator. Before the test, fill the pesticide box with 10L water, keep the liquid pump power unchanged during the test, and record the time when the 10L water completely flows out with a stopwatch. The actual spray volume is the ratio of 10L water to the monitored spray time. Through formula (7), the spray volume monitoring value is compared with the actual spray volume to calculate the spray volume monitoring error.

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$$\eta = \left|\frac{Q''t''}{5} - 1\right| \times 100\% \tag{7}$$

Where, Q'' —spray volume monitoring value, mL/s; η —spray rate error; t'' —spray time monitoring value, s.

3.2.4 Liquid level monitoring test

The pesticide box was pre-loaded with a certain amount of liquid, and the liquid height was measured with a graduated scale before taking off, which is regarded as the actual value. During the test, the UAV was placed in a hovering state, and the liquid level was monitored using monitoring system. The test consisted of 12 groups of three-level tests, each test was repeated 3 times, and the average value of the monitoring values were taken as the effective value. The monitored value was compared with the actual value through formula (8) to obtain liquid level monitoring error.

$$\phi = \left|\frac{h'}{h_0} - 1\right| \times 100\% \tag{8}$$

Where, ϕ —liquid level monitoring error; h' —liquid level monitoring value, mm; h_0 —actual liquid level, mm.

3.2.5 Variable control test

Before the test, the pesticide box was filled with 10L liquid, the spray width was set to 5 m, and the flight height was set to 3m. In the test, the spray track was arranged on the test site, and the UAV was flown according to the spray track during the test. The test took flight speed and spray rate per hectare as the variable factors, and two-factor five-level test was performed. The flight speed data are: 2m/s, 3m/s, 4m/s, 5m/s, 6m/s, and the data of spray volume per hectare are: 9L, 10.5L, 12L, 13.5L, 15L. Record the spray time during the test. The actual spray volume per hectare is the ratio of the total spray volume to the spray area. Combining equation (2), the calculation formula of the actual spray volume per hectare can be obtained as shown in equation (9).

$$C_0 = \frac{2\times10^4}{vt} \tag{9}$$

Where, C_0 —the actual spray volume per hectare, L/hm2.

By comparing the actual spray volume per hectare and the set spray volume per hectare based on formula (10), the variable control error is obtained. If the error is within ±10%, it can be considered that the actual demand of aerial variable spray is met [25].

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$$\sigma=\left(\frac{2\times10^{4}}{vtC}-1\right)\times100\% \tag{10}$$

Where, C —set spray volume per hectare, L/hm2; σ —spray volume error.

IV. RESULTS AND ANALYSIS

4.1 Track Monitoring Test

The track monitoring results are shown in Fig. 5. The green area in the figure is the spray area, the red line is the planned flight route, and the blue line is the actual flight track.

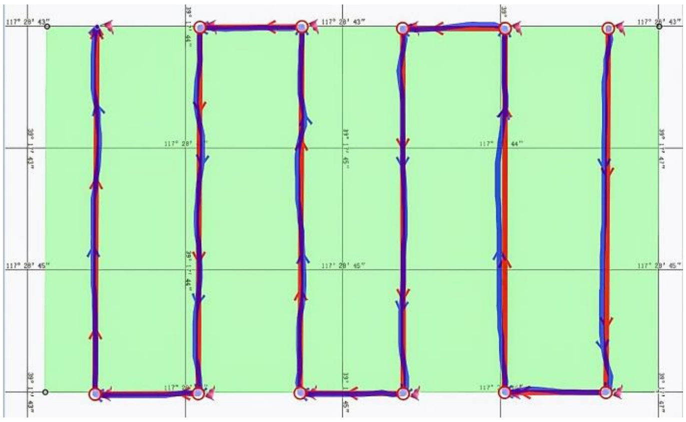

Fig 5: flight track diagram

12 coordinate points on the boundary of the spray area were selected for analysis. The flight track error is shown in Fig. 6.

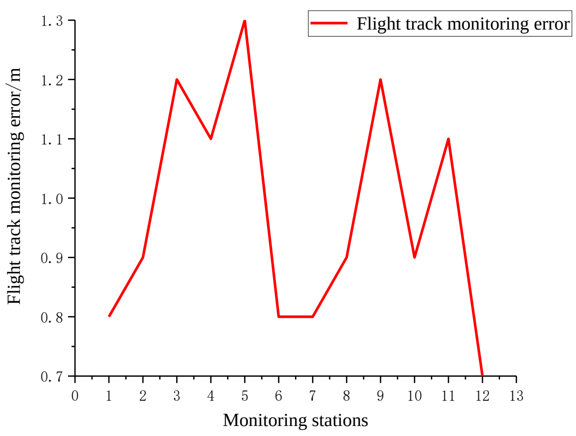

Fig 6: error analysis of flight track monitoring test

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It can be seen from the flight track diagram in Fig.5 that there is a certain error between the monitored track and the planned track. Since track monitoring relies entirely on GPS to collect coordinate points, plus certain errors in GPS positioning, monitoring errors are inevitable. It can be seen from Fig. 6 that the error of the track monitoring test is between 0.7~1.3m.

Since the track deviations are randomly distributed on both sides of the planned track, and the spray width is 5m during normal spray operation, so the average area change range can be obtained by formula (5) between 90.25%~109.75%, which is included in The interval is 90%~110%, so the monitoring system has a higher accuracy of track monitoring, and the monitoring error is within a reasonable range. The test verifies that the monitoring system has a high accuracy in UAV track monitoring to meet the needs of aerial spray.

4.2 Flight Speed Monitoring Test

The error analysis of the flight speed monitoring test is shown in Fig.7.

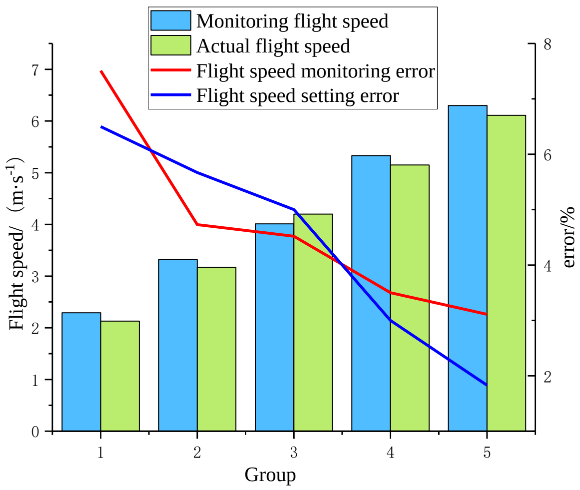

Fig 7: result of flight speed monitoring test

It can be seen from Fig. 7 that in each group of test, both the monitored flight speed and the actual flight speed are above the set flight speed, and the error shows a downward trend. This is because the UAV is empty and the battery is fully charged during the test, making the actual flight speed slightly above the set flight speed. Due to the continuous consumption of electrical energy during the test, the power is weakened. Moreover, with the increase of group, the set flight speed also increases, making the base of error calculation increased, so that both flight speed monitoring error and flight speed setting error show a downward trend.

The flight speed monitoring error is within 3.11%~7.51%, with an average error of 4.67%. The flight speed setting error is within 1.83%~6.5%, with an average error of 4.4%. The maximum flight speed error caused by monitoring error is 0.19m/s, while that caused by setting error is 0.20m/s. By comparison, the

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setting error exerts greater impact on the actual flight speed than the monitoring error. In the actual spray process, the flight speed will also be affected by the ambient wind speed, so the flight speed setting error will be greater. To conclude, the flight speed monitoring error is much smaller than the flight speed setting error, and the system's flight speed monitoring meets the needs of agricultural aerial spray monitoring.

4.3 Spray Volume Monitoring Test

The error analysis of the spray volume monitoring test is shown in Figure 8.

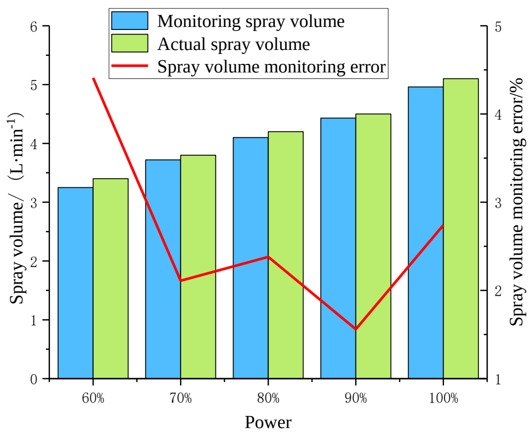

Fig 8: result of spray volume monitoring test

It can be seen from Fig. 9 that the system’s spray volume monitoring error is within 1.56%~4.41%, with an average error of 2.91%. The liquid pump has a big spray volume monitoring error when the power is 60%; after the power is increased, the error is small and relatively stable. The main reason is that when the liquid pump is working at low power, the pesticide liquid in the pipe has low flow rate and causes small impact force on the sensor, making the sensor unable to accurately monitor the actual spray volume. However, due to problems such as tightness of the connection between the liquid pump and water pipe, the voltage fluctuation and the accuracy of the flow sensor, errors always exist. When the flow monitoring error reaches the highest, the spray volume error per hectare is 4.41%, which is smaller than 10%, so it can meet the needs of spray volume monitoring in aerial spray. The standard deviation of the test is 0.9652%, indicating that the data dispersion is low and the data reliability is strong, so the needs of spray volume monitoring in aerial spray are met.

4.4 Liquid Level Monitoring Test

Analysis of liquid level monitoring test results is shown in Fig. 9.

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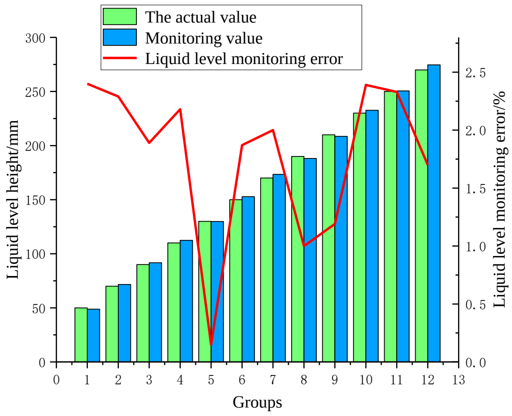

Fig 9: result of liquid level monitoring test

It can be seen from Fig. 9 that the error between system liquid level monitoring and actual liquid level measurement is between 0.15%~2.4%, with an average error of 1.78%. When the error is 2.4%, the liquid level monitoring error is 0.12cm. Since the UAV pesticide box has a maximum cross-sectional area of 900cm2, the maximal error of the residual pesticide liquid is 108mL. As the UAV pesticide box generally has a load capacity of 10L, the maximum residual pesticide liquid error accounts for 1.08% of the total pesticide liquid, indicating a small error.

From the line chart, it can be seen that the error value is less discrete, and the standard deviation is 0.6818%, indicating strong data reliability. In summary, liquid level monitoring has high accuracy to meet liquid level monitoring requirements of aerial spray.

4.5 Variable Control Test

Analysis of the variable control test results is shown in Fig 10.

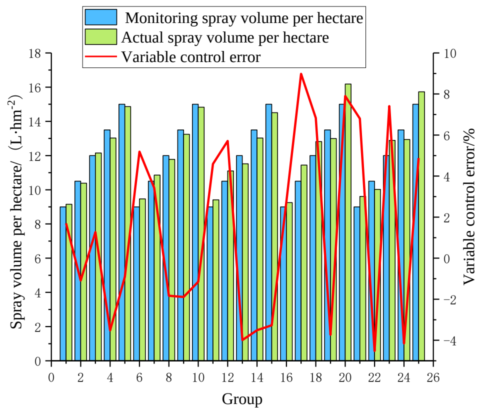

Fig 10: variable control test results

From the 25 sets of tests in Fig. 10, it can be seen that when the flight speed and spray volume per hectare are changed, the error between the actual spray volume per hectare and the set spray volume per

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hectare is between -4.52%~8.98%. It can be seen from the line chart in the figure that the variable control error is uniformly distributed on the two sides with "0" scale line as the axis, indicating high data reliability. The maximum error of variable control is 8.98%, which is less than 10%, indicating that the system can accurately adjust the spray volume according to the flight speed change under any spray volume per hectare, so that the actual spray volume per hectare is consistent with the set value, thus meeting the demand for spray volume control in aerial variable spray.

V. CONCLUSION

(1) A real-time monitoring system is designed for aerial variable spray, and the system hardware and software are elaborated in detail. The monitoring test verifies that the system has strong monitoring performance to meet the monitoring requirements of aerial spray. The monitoring test results show that the system error in track monitoring is between 0.7~1.3m, the flight speed monitoring error is between 3.11%~7.51%, the spray volume monitoring error is between 1.56%~4.41%, and the liquid level monitoring error is between 0.15%~2.4%. The errors are within a reasonable range, indicating that the system can accurately monitor the UAV operating parameters in real time.

(2) For UAV spray, a set of spray volume control algorithm is proposed. This algorithm can automatically adjust the spray volume when the flight speed changes to ensure that spray volume per unit area reaches the requirement. The test results show that when the flight speed and spray volume per hectare are changed, the system can adjust the spray volume accurately in a timely manner with an error between -4.52%~8.98%. It verifies that the system has high accuracy in spray volume control. The maximum error is 8.98%, which is smaller than 10% and meets the needs of aerial variable spray.

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