Research on Safety Control Method of Multi-rotor Unmanned Aerial Vehicle Under Super-Strong Wind Field

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Abstract. Due to the simple structure and lightweight of the Multi-rotor Unmanned Aerial Vehicle (UAV), it is easy to be affected by the wind field environment. The super strong wind may even cause the multi-rotor UAV to crash, so it is very important to ensure the safe of the multi-rotor UAV under the super-strong wind environment. However, researchers focus on improving the anti-disturbance performance of multi-rotor UAVs in wind field, and there are relatively few researches on safety control methods. Therefore, the research on safety control when the multi-rotor UAV cannot resist the wind is of significance. Firstly, this paper takes the lead in the behavior of multi-rotor UAVs in super-strong wind field. Secondly, the research proposes a wind-driven safety control method based on wind and an altitude-security control method based on online estimation. At last, the ways have verified by experiments that the safety of the aircraft has effectively ensured.

Keywords: Multi-rotor unmanned aerial vehicle · Super strong wind field · Wind-driven safety control method · Online estimation

1 Introduction

Due to its vertical takeoff and landing, fixed-point hovering, and strong maneuverability [1–3], multi-rotor unmanned aerial vehicle are widely used in civil and military field. However, the multi-rotor unmanned aerial vehicle is easy to affect by the wind

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field environment because of the small size, lightweight and the structural characteristics [4, 5]. Moreover, the variability of the wind field environment sometimes leads the multi-rotor unmanned aerial vehicle directly to crash due to the stall of the propeller. Therefore, it is of great significance to study the safety control problem of multi-rotor unmanned aerial vehicle in super-strong wind environment.

The design of safety control strategy for multi-rotor unmanned aerial vehicle in super-strong wind environment mainly includes two aspects: the design of the body safety control and the design of the altitude anti-disturbance control. For the safety control problem of multi-rotor unmanned aerial vehicle in super-strong wind environment, researchers are mostly focusing on the research of anti-disturbance control methods, but there are few studies on the safety control methods of the aircraft. In 2003, Civita linearized the multi-rotor unmanned aerial vehicle model at multiple equilibrium points and achieved a wide range of stability by designing the controller, effectively achieving disturbance suppression [6]. However, the performance of multi-rotor unmanned aerial vehicle has greatly affected by local linearization. In recent years, the three-dimensional fuzzy PID method adopted by researchers has realized the stable control of the attitude and the precise trajectory tracking control, and effectively realized the disturbance suppression of the output signal [7], but this method has only used to suppress the disturbance caused by the parameter fluctuation. The ability to suppress external environmental disturbances is not strong. In addition, the combination of intelligent algorithms and UAVs can also achieve the suppression of disturbances. In 2014, Lee [8] proposes an inversion technique for dynamic models based adaptive neural networks, which effectively improves the performance of PD controllers and improves them. The anti-disturbance capability of the multi-rotor unmanned aerial vehicle system. In the same year, by combining the genetic algorithm with the identification of multi-rotor UAV model parameters, the influence of external disturbance on the parameters of multi-rotor UAV model is greatly reduced, and the multi-rotor UAV model is guaranteed to be reliable, which is proposed by Yang [9]. However, the calculation time of the intelligent algorithm is long, and it is not applicable to the UAV system with high real-time requirements. Therefore, it is urgent to propose a safety control method and a high anti-disturbance control method in a super-strong wind environment to ensure the flight safety of the multi-rotor UAV.

The paper takes the design of the safety control method of multi-rotor UAV in super-strong wind environment as the research topic. Firstly, a complete safety control strategy have proposed for the safety control of multi-rotor UAV in super-strong wind environment. Then two strategy have proposed to ensure the flight safety, the method of body safety control has used to ensure the attitude safety of the multi-rotor UAV, an altitude safety constant control method has used to ensure the altitude safety of the multi-rotor UAV during flight, and the reliability of the scheme has fully verified by experiments in various parts.

2 The Design of Safety Control Strategy

The multi-rotor UAV should remain altitude constant and attitude stable for practical flight in the super-strong wind field. Therefore, the core of the safety control strategy is to ensure that the aircraft's own attitude is stable and altitude constant.

In order to achieve this design goal, first, it is necessary to distinguish the control loop structure that should has added and abandoned at this time. When the multi-rotor UAV is working in the super-strong wind environment, if the UAV cannot resist the disturbance of wind, the field is no longer suitable for mission execution, and UAV should turn to ensure the safety of the aircraft. The effect of the wind field disturbance on the UAV is mainly to affect the output of the UAV's velocity control loop and the output of the attitude control loop. While in the safety control, the wind field should have changed to the attitude control loop. The output disturbance has regarded as the driving force, so that the three-axis torque has determined by the wind field, and the posture angle and the flight speed have reduced by actively adjusting the attitude angle to adapt to the direct effect of the wind field force on the body. In addition, the wind in the vertical direction will eventually act on the multi-rotor UAV in the form of force, which will eventually change the altitude of the UAV and intimidate to the safe of the UAV. Therefore, the altitude change of the multi-rotor UAV should has reduced as much as possible In the process of safety. Therefore, the wind force at this time should be a disturbance power that needs to suppress instead of the driving force.

The designed safety control scheme show in Fig. 1, and τ_h indicates the disturbance caused by the wind field disturbance to the altitude control loop of the multi-rotor UAV, τ_z indicates the disturbance torque generated by the wind field disturbance to the attitude control loop of the multi-rotor UAV.

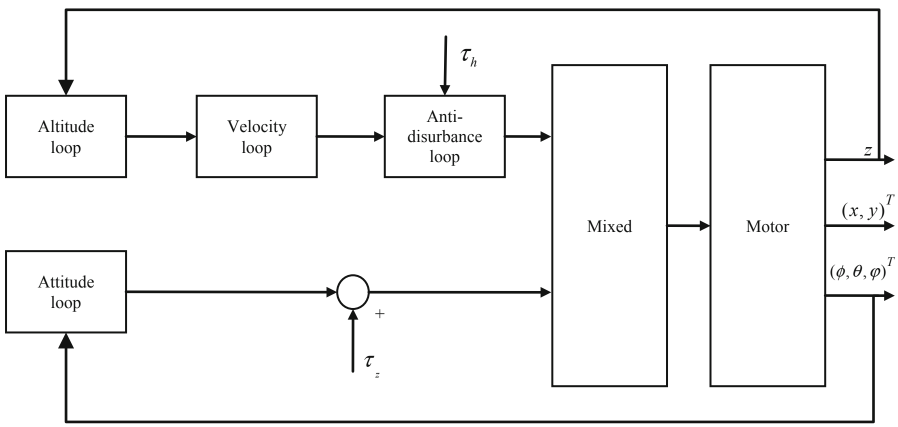

Fig. 1. The design of security control schemes.

3 Design of Body Safety Control Method

3.1 The Method Design of the Body Safety

The influence of wind field force on the multi-rotor UAV includes mainly two aspects. One is to change the induction speed at the propeller paddle, and the other is to change the force directly acting on the body. For both of them, the angle between the propeller and the wind is directly determined, that is to say, the attitude angle of the multi-rotor UAV has determined. Therefore, the wind field force has relationships with the attitude angle.

Because the wind field is unpredictable and changes frequently, the wind field force is uncontrollable. However, since the wind field force has relationships with the attitude angle, the attitude angle can adjust to adapt to the wind field to reduce the influence of the wind field to the multi-rotor UAV. Therefore, it is possible to adjust the attitude to adapt to the wind field force to ensure the safety of the multi-rotor UAV.

Assuming that the wind field force is T and the influence of the wind field environment to the multi-rotor UAV all acts on the pitch channel. Which leads the multi-rotor UAV to generating acceleration a_x along the axis x of the body coordinate system and acceleration a_y along the axis y of the body coordinate system, and the multi-rotor UAV has a tensile force F due to the high-speed rotation of the propeller. The force analysis diagram shows in Fig. 2.

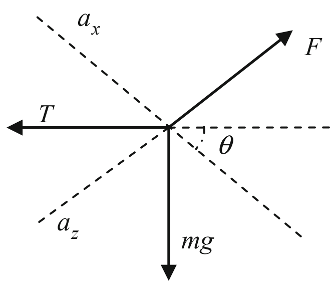

Fig. 2. Diagram of wind analysis

Due to the combination of the wind field force, the pulling force generated by the propeller and the gravity, the acceleration along the axis x and y of the body coordinate system has generated. In order to analyze the wind field force, the acceleration has decomposed parallel to the horizontal direction and perpendicular to the horizontal direction as shown in Fig. 3.

Two equations of Eqs. (1) and (2) have obtained.

$$T - F\sin\theta = m(a_x\cos\theta + a_z\sin\theta) \tag{1}$$

$$F\cos\theta - mg = m(a_x\sin\theta - a_z\cos\theta) \tag{2}$$

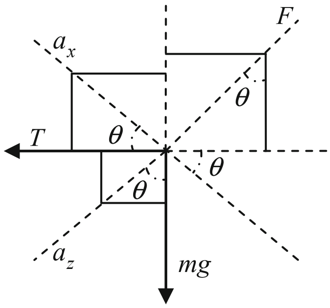

Fig. 3. Diagram of wind analysis

The above two equations can be solved in tandem to obtain an expression about the wind field force, as shown in Eq. (3).

$$T\cos\theta - mg\sin\theta = ma_x \quad (3)$$

Assuming that the combined force of wind field force and gravity is T_∞, and the Eq. (4) can have obtained.

$$T_\propto = \sqrt{(mg)^2 + (T)^2} \quad (4)$$

Moreover, the Eq. (5) can have obtained.

$$\frac{T}{T_\propto}\cos\theta - \frac{mg}{T_\propto}\sin\theta = \frac{ma_x}{T_\propto} \quad (5)$$

Assuming that the angle between the force produced by the wind field and the gravity is β. Moreover, the Eqs. (6) and (7) have obtained.

$$T_\propto \sin\beta = T \quad (6)$$

$$T_\propto \cos\beta = mg \quad (7)$$

The Eq. (8) has simplified by the Eq. (5) as shown below.

$$\sin\beta\cos\theta - \cos\beta\sin\theta = \frac{ma_x}{T_\propto} \quad (8)$$

The expression obtained by the above equation to obtain the pitch angle is as shown in the Eq. (9).

$$\theta = \beta - \arcsin\frac{ma_x}{T_\propto} \quad (9)$$

However, the attitude angle has relationships with the wind field force. To adapt to the wind field by the attitude angle to reduce the fluctuation of the attitude angle of the multirotor UAV, it is necessary to be able to determine the magnitude of the wind field force at any time. Therefore, The kinematic equation of the multi-rotor UAV must have analyzed with the wind filed.

$$m\dot{v} = -RF + mge_z + Te_x \tag{10}$$

Since the wind field force is horizontal, the kinematics equation in the horizontal direction is as follows.

$$ma_x = -e_x^T RF + T \tag{11}$$

The magnitude of the wind field force can have solved as shown in Eq. (12).

$$T = ma_x + e_x^T RF \tag{12}$$

The attitude angle of the multi-rotor UAV can maintain under the wind field can have calculated from the Eqs. (5) and (12). The multi-rotor UAV can adjust the attitude angle in time to adapt to the current wind field.

3.2 Experimental Design and Data Analysis

Two sets of experiments are required to verify the reliability under super-strong wind conditions, and one set of experiments represented the situation corresponding to the UAV trying to maintain the current position even if it had subjected to the super strong wind environment. The actual situation corresponding to another set of experiments is that the multi-rotor UAV feels that the wind is too large to give up the position automatically, and instead uses attitude control to ensure the safety of the multi-rotor UAV itself.

In order to simulate the super-strong wind environment, it is necessary to ensure that the wind speed is large enough. For this reason, we use the JGFS7-4 fan. Moreover, the wind turbine can generate wind speeds of 17.7 m/s, which is enough to simulate the super wind field.

In the actual experimental process, in order to simplify the research, the head of the UAV and axial flow of the fan keep parallel in the initial state. In addition, during the experiment, the wind field disturbance has kept as far as possible on the pitch channel of the multi-rotor UAV, so that the disturbance of the wind field to the multi-rotor UAV was all manifested by yaw. Among them, the yaw angle curves of the two sets of experiments have shown in Figs. 4 and 5, respectively.

Among them, the red line represents the desired heading angle; the black line represents the actual heading angle. For the first set of experiments, combined with Fig. 4 and the actual flight experiments, the fan has turned on at the end of 115 s. During the period of 115 s–149 s, the deviation between the actual heading angle of the multi-rotor UAV and the desired heading angle reaches 0.5 radians. In addition, the

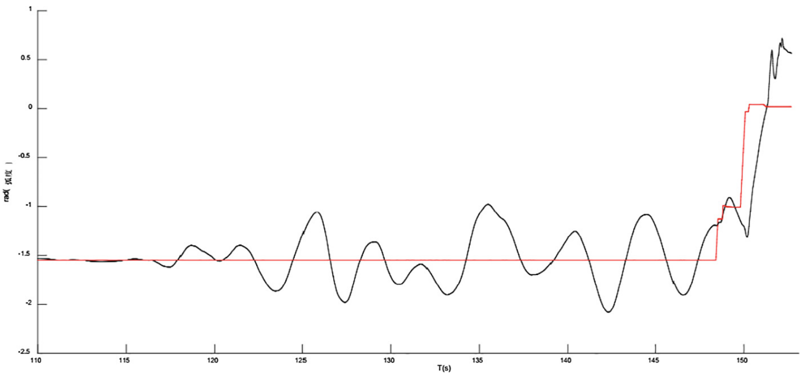

Fig. 4. Heading angle curve of the first set of experiments (Color figure online)

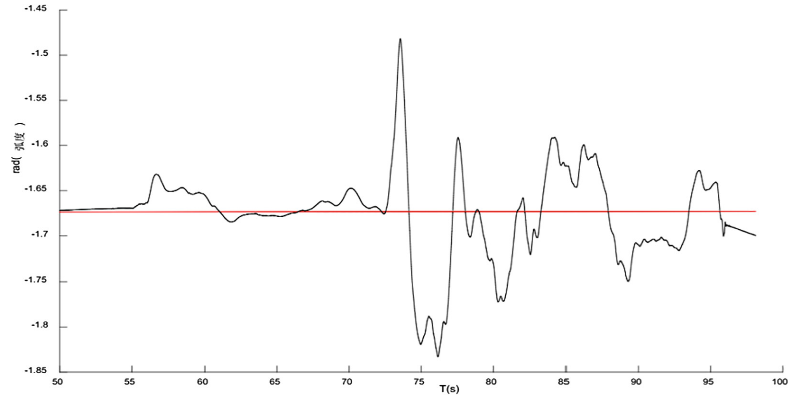

Fig. 5. Heading angle curve of the second set of experiments (Color figure online)

entire yaw angle showed a tendency to oscillate, which led to the loss of control of the multi-rotor drone at the end of 149 s, which eventually led to the crash of the UAV.

For the second set of experiments, combined with Fig. 5 and the actual flight experiments, it can be seen that the fan starts at the end of 70 s, and the deviation between the actual heading angle of the multi-rotor UAV and the desired heading angle reaches the maximum during the period of 70 s–77 s, which is 0.2 radians. And during the period of 77 s–98 s, the difference between the actual yaw angle and the expected yaw angle gradually decreases, and the yaw angle of the multi-rotor UAV exhibits a tendency to converge toward the desired yaw angle.

Combined with the actual experimental results, the multirotor UAV that always keeps the fixed point eventually crashes, and the multi-rotor UAV ensures the safety of the body by timely adopting the safety control method, further illustrating the reliability of the design method.

4 The Method Design of Altitude Constant Control

4.1 Feasibility Analysis of High Anti-disturbance

In order to collect wind speed data for the wind field, it is first necessary to select a reasonable anemometer. Here, we use the 3D anemometer sensor produced by Gill. Among them, the measurement accuracy of the three-dimensional anemometer sensor can be achieved 0.01 m/s, and the sampling frequency can be achieved 20 Hz.

During the sampling process, the wind speed sensor has first installed on a fixed iron frame with a length of 1.4 m, and then communicated with the computer through the serial port for data sampling. Moreover, the time fixes at 2 min each time.

Through the observation of the natural wind field for two months, which finally finds the regularity of the wind field data. For the data analysis, some data from 10:00 am to 3:00 pm on October 14, 2018 has selected as Table 1.

Table 1. Wind field data sheet.

x	*Y*	*z*	*horize*	*horize/z*
2.25	2.51	0.28	3.37	12.2
2.07	2.13	0.5	2.97	5.89
2.30	2.51	0.89	3.41	3.83
1.52	1.45	0.33	2.1	6.34
2.35	1.88	0.09	3.01	32.35
1.41	1.1	0.42	1.79	4.27
0.73	0.84	0.51	1.11	2.18
1.35	6.99	1.15	7.12	6.19
2.79	0.72	0.11	2.88	25.25

Where *horize* represents the wind speed in the horizontal direction and its calculation formula is as shown in (13).

$$horize = \sqrt{x^2 + y^2} \tag{13}$$

It shows that the combined wind speed in the horizontal direction is at least double the wind speed in the vertical direction from the data. Due to this unevenness of the wind field, even the horizontal wind speed reaches a certain wind resistance limit due to the vertical wind speed. Vertical wind speed is relatively low, so there is still a large margin, so that the possibility of disturbance suppression of the height control loop of the multi-rotor drone in the wind field environment is greatly improved.

4.2 Design of Altitude Disturbance Control Method

He [10] proposed a disturbance suppression method based on first-order low-pass filter for low-frequency disturbance suppression of electromechanical systems in the robust and predictive control of nonlinear electromechanical systems, and achieved success through experiments. Therefore, with the help of similar ideas, this paper proposes an altitude control method based on online estimation. The online estimation of the altitude anti-disturbance control method directly compensates for the vertical acceleration by introducing a first-order low-pass filter to resist the wind field disturbance.

Assuming that the low-pass filter is f_h, the output tension of the vertical speed control loop is F_h, and the vertical acceleration generated after the disturbance is a_z, the altitude-disturbance control diagram shows in Fig. 6.

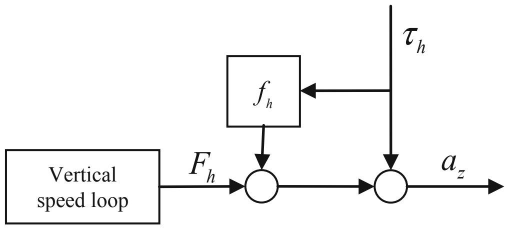

Fig. 6. Altitude anti-disturbance control chart

F_h Can be decomposed into two parts of force, F_m is used to balance gravity, and F_a produces vertical acceleration. Among them, the expression is as shown in (14).

$$F_h = F_a + F_m \tag{14}$$

The equation shown in (15) can have obtained from the above transfer function.

$$F_a - f_h \tau_h + \tau_h = ma_z \tag{15}$$

The expression for simplification of the wind field disturbance shows in (16).

$$\tau_h = \frac{ma_z - F_a}{1 - f_h} \tag{16}$$

Thus, an expression of the amount of feedback of the disturbance has obtained as shown in the Eq. (17).

$$v_h = \frac{f_h}{f_h - 1}(ma_z - F_a) \tag{17}$$

Since F_a and F_h are related, an expression of the feedback amount v_h can be further obtained as shown in the Eq. (18).

$$v_h = \frac{f_h}{f_h - 1}(ma_z + mg - F_h) \tag{18}$$

4.3 Determination of Low Pass Filter Parameter

In order to determine the low-pass filter parameters, data acquisition has performed on the wind field data at a distance of 2 m from the fan, and the spectrum of the wind field data is as shown in Fig. 7.

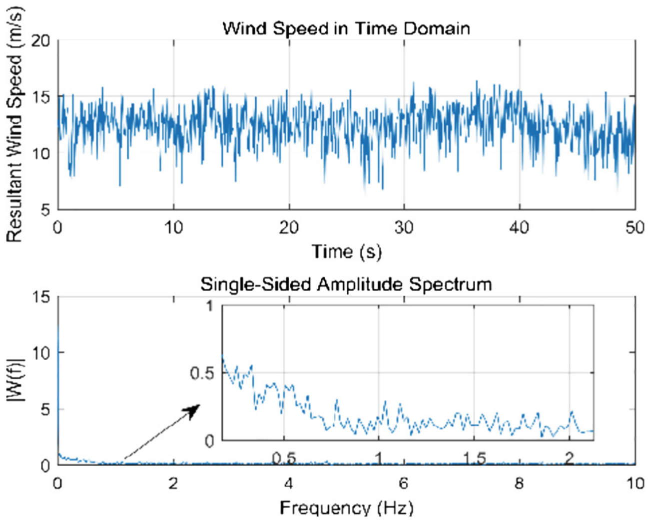

Fig. 7. Spectrogram of wind

From Fig. 7, in addition to the large amplitude at the position where the frequency is zero, there is a relatively large amplitude at a frequency of 0.2 Hz, and the amplitude is small at other frequency segments. Taken together, to suppress wind disturbances, the frequency of suppression should not be lower than 0.2 Hz.

The form of the low pass filter f_h is as shown in the Eq. (19).

$$f_h = \frac{a}{s+a} \tag{19}$$

The transfer function a of the wind field disturbance affecting the multi-rotor UAV is as shown in Eq. (20).

$$G_h = 1 - f_h = \frac{s}{s+a} \tag{20}$$

According to its frequency characteristics, a is the cutoff frequency, and it has a good inhibitory effect on disturbances with a frequency below a. Since the wind disturbance of 0.2 Hz must have suppressed, the value of the cutoff frequency cannot be less than 0.2, so the cutoff frequency can take as six, as shown in the Eq. (21).

$$a = 6 \tag{21}$$

The form of f_h is as shown in the Eq. (22).

$$f_h = \frac{6}{s+6} \tag{22}$$

Therefore, the expression of the feedback amount could have expressed as shown in the Eq. (23).

$$v_h = 6\int (F_h - ma_z - mg)dt \tag{23}$$

4.4 Experimental Design and Data Analysis

During the experiment, the UAV can be hovered at the tuyere position, and then experiments with no wind disturbance compensation and wind disturbance compensation have performed. The altitude deviation comparison has used to judge the feasibility of altitude anti-interference control.

In the first set of experiments, the multi-rotor UAV flew 2 m from the axial fan and the altitude was about 1 m and kept hovering. In addition, the fan turned off after a period. Among them, the altitude change map drawn based on the data obtained by the experiment shows in Fig. 8. Among them, the black line represents the actual altitude curve of the UAV, and the red represents the desired altitude curve.

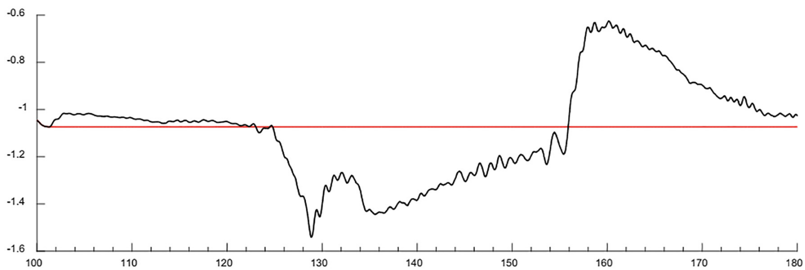

Fig. 8. Map of the altitude change without controller (Color figure online)

During the period of 100 s–124 s, the fan has not been turned on, and the multi-rotor UAV hovering around the desired altitude of 1 m, wherein the maximum deviation is 10 cm.

At the end of the 124 s, the fan has turned on, and the desired height does not change at this time, but the actual altitude is greatly deviated from the expected altitude. The maximum deviation is 50 cm, the average deviation is 30 cm, and it is always below the desired altitude. In addition, the altitude of UAV is extremely unstable.

In the second set of experiments, the multi-rotor UAV continue to keeping distance from 2 m to the axial fan and the altitude was about 1 m and kept hovering, and the altitude disturbance compensation has performed, and the fan had turned off after a period. Among them, the altitude change map drawn based on the data obtained by the experiment shows in Fig. 9.

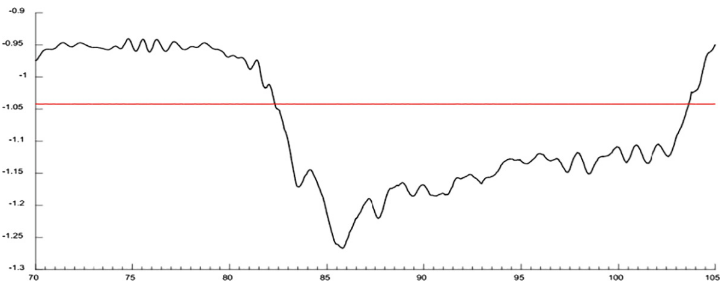

Fig. 9. Map of the altitude change with controller (Color figure online)

During the period of 70 s–82 s, the fan has not been turned on, and the multi-rotor UAV hovering around the desired altitude of 1 m, the maximum deviation is 10 cm.

At the end of the 82 s, the fan had turned on. The expected altitude did not change at this time, but the actual altitude began to change, but the deviation from the expected altitude was not large. Even the maximum deviation reached 20 cm, and the average deviation reached 15 cm.

This situation is clearly more stable than the first set of control experiments without altitude compensation. This further demonstrates the reliability of the design.

5 Conclusion

Based on the behavior analysis of multi-rotor UAV in super-strong wind environment, this paper proposes a safety control strategy for multi-rotor UAV in super-strong wind environment, and focuses on the methods of attitude stable control and altitude constant control. In the design of safety control method, a body safety control method based on wind driven adaptive wind field environment is proposed. In the design of altitude constant control method, an altitude anti-disturbance control method based on online estimation is proposed. The experimental results demonstrations of the two parts demonstrate the reliability of the proposed safety control scheme.

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