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Analysis on Attitude Fluctuation in Vertical Descent of Multi-rotor UAVs

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Abstract. In continuous vertical descent, multi-rotor UAVs' attitude will meet the problem of attitude fluctuation and tends to divergence. The problem comes from the flight controller instead of vortex-ring state. Based on an eight-rotor UAV's nonlinear model in hovering mode, the control law is analysed by using transfer function. The first reason is that the inner ring and outer ring bandwidths of the PID cascade controller do not match well. And the other one is that the lower linear operating point and lower average rotor speed during descent lead to less thrust and torque per propeller, which make it more difficult to resist wind disturbances. By adjusting the position loop's parameters in descent, the eight-rotor UAV reduced the requirement of horizontal position accuracy, and the stability of horizontal attitude control increased, which finally obtained a better performance.

1. Introduction

Multi-rotor UAVs have the ability to hover and descend vertically. But in certain application, for example, multi-rotor UAVs descending vertically from a height more than 1000 meters, it was found that the eight-rotor UAV was easy to encounter attitude fluctuations in continuous descent. For this phenomenon, one probable reason is that multi-rotor UAVs may encounter the vortex-ring state, another reason could be the unsuitable flight controller.

For the first reason, if a multi-rotor UAV descends vertically and rapidly, the rotors may fall into turbulence, in which it will suffer from severe thrust fluctuation. And this unsteady aerodynamic state usually leads to severe attitude fluctuation on multi-rotor UAVs. In engineering practice, reference[1] gives a reasonable criterion of vortex-ring state boundary for helicopter. Reference[2] proposes a method of descending with forward flight for multi-rotor UAVs, which can help reduce the probability of encountering the vortex-ring state. But this method needs a wide horizontal airspace for continuous forward flight. Actually, according to the practical boundary in reference [1], we limit the UAV's maximum descent rate at 2 m/s to avoid being caught in vortex-ring state. But there are still attitude fluctuations in vertical descent experiment. So, the vortex-ring state can be excluded as the main factor. And we turn to consider if the problem comes from the flight controller.

Most multi-rotor UAVs' flight controller use cascade PID control law in four control channels (pitch, roll, yaw and height) [3, 4]. PID controller is robust and adaptable [5] which permits the object deviating from original linear working point. So it is possible to use the same parameters for different flight modes (hovering, forward flight and vertical descent) of multi-rotor UAVs. However, a multi-rotor UAV's linear working point will change in different rates of descent. For this case, using the same set of control law is convenient in engineering practice but may not achieve a perfect performance for different flight modes [6]. Especially complex atmospheric environment, like wind shear, can cause oscillation when the flight controller has insufficient control margin. And it will ultimately lead to a loss of control of multi-rotor UAVs.

2. Model Linearization and Control Law Design for Multi-rotor UAVs

2.1. Multi-rotor UAVs' Model and Control Law Design

In a project, the nonlinear model of a centrosymmetric eight-rotor UAV was established. Based on the dSpace system, a Hardware-in-loop simulation platform was built to roughly test PID parameter and verify the program logic for the flight controller. In this process, the most difficult thing is to get each rotor's dynamic nonlinear model. It can be solved by referring to the method of modelling a helicopter's main rotor [7].

To simplify the control law design, we linearize the nonlinear model of the eight-rotor UAV at hovering working point. The high-order minor terms of the linearized expression represent for interactions between the four control channels, which can be ignored. So, multi-rotor UAVs' four channels can be controlled in a decoupled manner.

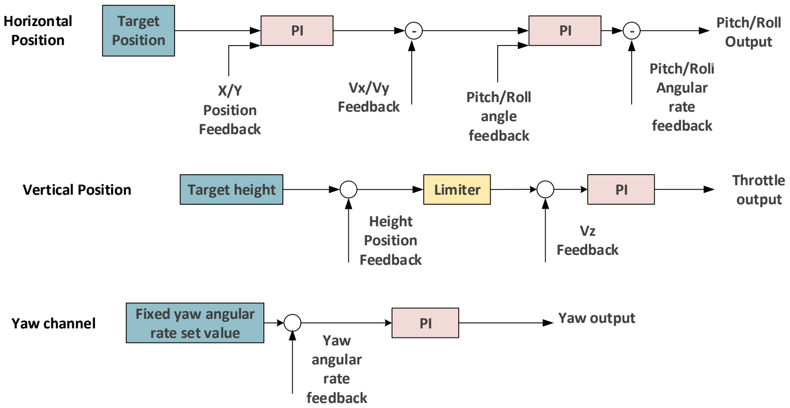

Figure 1. Control law of multi-rotor UAVs in hovering mode

As shown in figure 1, in pitch and roll channels, the eight-rotor UAV uses the same control law during the vertical descending and hovering. Inner ring is attitude loop and it uses PI controller with angular rate damping. The outer ring is position loop and it uses PI controller with velocity damping. So, there is a two-stage PID cascade controller in pitch or roll channels. For the vertical channel, the UAV adopts a PI controller in the command of descent rate whose setting value is guided by altitude position. Finally, four channels' output value will be normalized and converted into rotor speed setting value for each propeller.

2.2. Analyzing Control Structure in Transfer Function

Using the MATLAB linearization kit, the linearized expressions of four channels are obtained and the open-loop transfer function for the angular rate in roll/pitch channel can be written as equation (1).

$$Gqlon(s) = \frac{308.7s^2 + 3.365s}{s^3 + 6.351s^2 + 0.06911s + 0.6396} \tag{1}$$

Based on the transfer function of $Gqlon(s)$, the structure of the inner-loop can be constructed and is shown in figure 2. Then the attitude loop's transfer function can be represented by equation (2). By zero-pole analysis, equation (2) can be approximately equivalent to a second order system, written in equation (3).

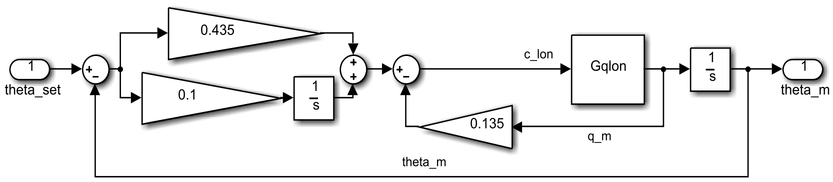

Figure 2. attitude-loop structure

$$Gtheta(s) = \frac{134.3s^2 + 1.772s + 0.003365}{s^4 + 48.02s^3 + 134.8s^2 + 2.412s + 0.003365} \tag{2}$$

$$G_\theta(s) = \frac{133.9}{s^2 + 48.01s + 133.9} \tag{3}$$

Comparing the two equation (2) and (3) in bode diagram (Figure 3), it demonstrates that the function $G_\theta(s)$ can be a substitute for $Gtheta(s)$. That is to say, the inner ring (attitude closed loop) of multi-rotor UAVs can be equivalent to a second-order system.

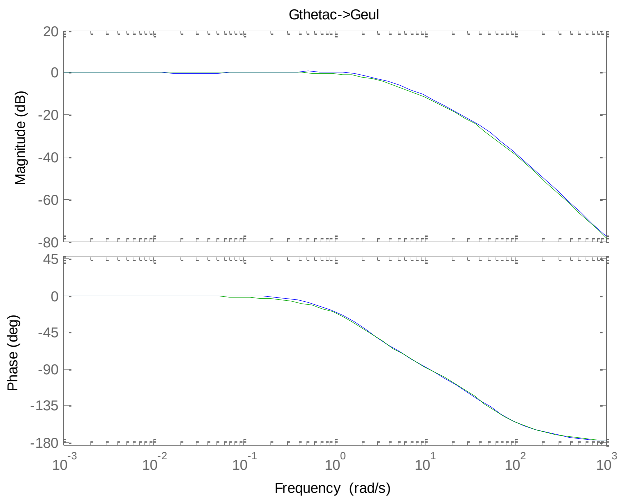

Figure 3. Bode plotting comparison between Gtheata(s) & Gθ(s)

Based on the transfer function of $G_\theta(s)$, the outer-loop is constructed in figure 4 and its transfer function is expressed in equation (4), which can be figured out that the closed-loop system has a damping oscillation period in 3.228 seconds.

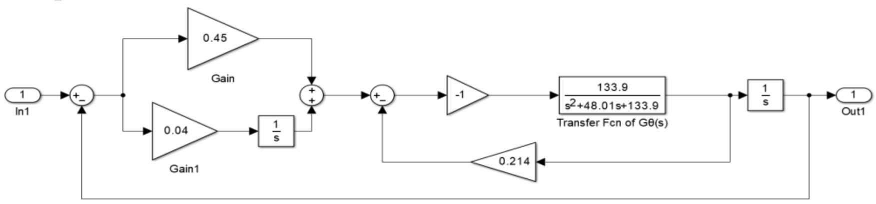

Figure 4. Position closed loop controller structure

$$Gpc(s) = \frac{53.56s + 5.356}{s^4 + 48.01s^3 + 105.3s^2 + 53.56s + 5.356} \tag{4}$$

2.3. Attitude Tracking Curve Comparison between Hovering and Descent Mode

The control law depicted in section 2.2 is used to control the eight-rotor UAV in different flight modes. The figure 5 shows that the real pitch value keeps tracking the setting value closely in hovering mode in real test. The figure 6 is the pitch curve at a descent rate of 2 m/s, which records the severe attitude oscillation in pitch channel.

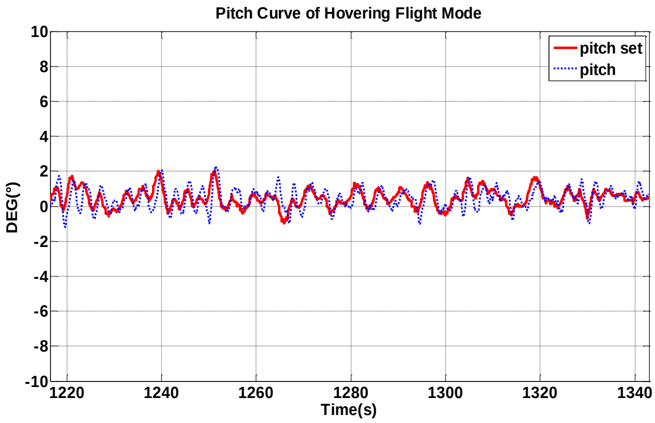

Figure 5. Pitch curve of hovering mode

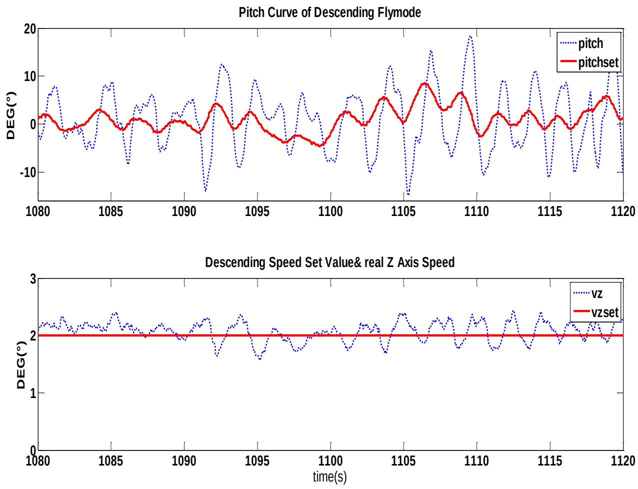

Figure 6. Pitch curve and vertical velocity curve in descent

3. Improvement of Control Law in Descent

3.1. Analysis of Attitude Oscillation in Descent

The attitude tracking performance in hovering mode is good, and this shows that there is little possibility of inner ring causing fluctuation problems. So the attitude fluctuations in descent are mainly attributed to two aspects.

The first reason is that the inner ring and outer ring's bandwidths do not match well. Position loop output is the external incentive of attitude loop. When the external incentive's frequency is close to the inner ring's inherent frequency, it will cause resonate in attitude curve. And if the external incentive frequency is higher than inner loop's bandwidth, it will cause the inner controller's phase delay which can also lead to a drastic attitude oscillation. In engineering practice of PID controller, the inner ring bandwidth should normally be five times that of the outer ring. Based on the transform function, we figure out the attitude loop and the position loop's bandwidths, which are 2.69 rad/s and 0.95 rad/s respectively. To some extent, this indicates that the improper position loop's PID controller parameters cause attitude fluctuation.

Secondly, average rotor speed of the eight-rotor UAV is lower than that in hovering mode. The change of the throttle operating point in descent has a different linear working point. However, each rotor's thrust and torque are lower than that in hovering mode. When using the PID parameters adapted to hovering mode to control the descent process, the eight-rotor UAV is more susceptible to the effects of atmospheric disturbances in descent, resulting in attitude fluctuations.

3.2. Experiment Result

After analysis, the proportion item of outer ring's PI controller was decreased and the integration item was nearly removed. The eight-rotor UAV did a vertical descending experiment again. Figure 7 gives the pitch curve in an experiment after adjusting parameters. And one can see that the attitude curve tracking characteristic is improved in figure 7. Also, Z-axis velocity is less affected by attitude fluctuation.

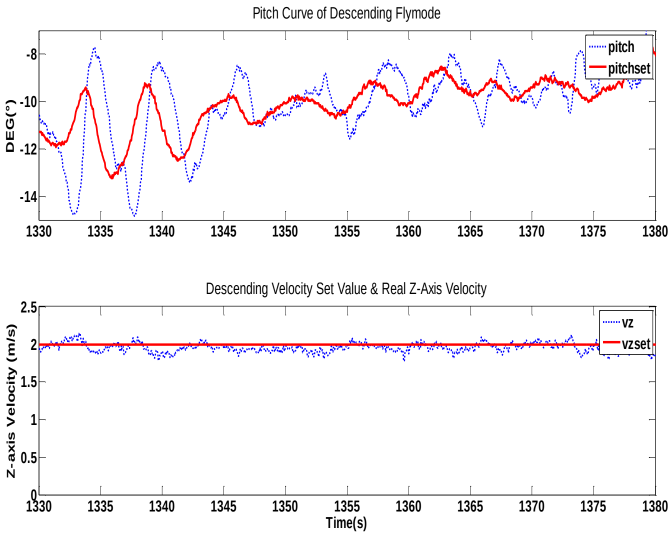

Figure 7. Pitch curve and vertical velocity curve in descent after adjusting controller parameters

4. Conclusion

This work studies the problem of attitude fluctuation in descent of multi-rotor UAVs. From the experiment result, one can see that the mismatch bandwidths and inappropriate controller parameters caused the problem. Using PID cascade controller, the horizontal position precision can be reduced in exchange for the stability of horizontal attitude control. After adjusting the position loop's parameters, the UAV achieve a better stability in continuous descent.

Acknowledgements

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