Research on The Principle And Optimization of Multi-Rotor Aircraft

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Abstract. In today's society, unmanned aerial vehicles are becoming increasingly mature and popularized with each passing day. Compared with other fixed-wing aircraft, helicopter-based aircraft and multi-rotor aircraft have emerged like bamboo shoots because it can vertically take off and land, be easy to manufacture, easy to control, and can complete all kinds of attitude flights. While in multi-rotor aircraft, multi-rotor aircraft with four-axis and even multiples occupy almost 100% of the market. This is because the multi-rotor aircraft of even number times is characterized by easy production, simple principle, and so on. However, if it is not sufficiently optimized in practical application, its anti-jamming ability and adaptability in flight are still not very ideal. In this paper, we will analyze its working principle represented by four axes, and try to further optimize the design of it.

1 Working Principle of Quad-rotor

As multi-rotor aircraft are powered by motors and the rotation of motors will cause rotation of the equipment itself, the quad-rotor places its motors at each top of the four sides of the aircraft body, the four rotors are at the same height and plane, the structures of the four rotor wings are exactly the same, and the space in the middle is used to place the flight control chip and the electronic equipment. The structure and form is shown in fig.1.

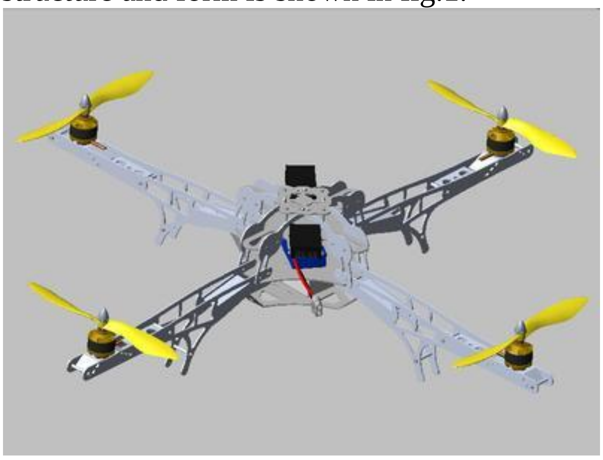

Figure 1. The Structure Snd Form

Under normal circumstances, when one axis of the quad-rotor rotates counterclockwise, another axis rotates clockwise, so when the quad-rotor flies, the autorotation effect will be eliminated. While changing the rotate speed of the four motors can realize the movement of the four axes in all directions. The quad-rotor is a six-channel aircraft with only four force inputs and six flying states, so it is an under-actuated system.

In the following analysis, the position of the arrow represents the change in motor speed. If it is above the rotor wing, it means that the rotate speed is increased; if it is below the rotor wing, it represents that the rotate speed is reduced. Its six specific flight attitudes are analyzed as follows:

1.1 Vertical movement. Meanwhile, increase the rotate speeds of the four motors and enhance the lift force, and when the total lifting force generated by the quad-rotor is larger than the gravity force, the quad-rotor can rise off the ground; on the contrary, reduce the rotate speeds of the four motors, the quad-rotor will descend vertically. When it is not disturbed by the outside and the power produced by the motors is equal to the weight of the quad-rotor itself, and it can maintain a stable hover.

1.2 Pitching movement. The speed of Motor 1 increases and the speed of Motor 3 decreases (their variations are equal), the rotate speeds of Motor 2 and Motor 4 remain constant. As the lift force of Motor 1 increases and the lift force of Motor 3 decreases, resulting in the imbalance of lift forces, then the quad-rotor body will rotate around the y axis on its own. Undoubtedly, the operator can also reduce the speed of Motor 1 and increase the speed of Motor 3, the body can still rotate around the y axis, thus realizing the pitching movement of the aircraft.

1.3 Rolling movement. As with pitching movement, change the speeds of Motor 2 and Motor 4 in the opposite direction, the speeds of Motor 1 and Motor 3 still remain constant, then the four axes can rotate around the x axis on their own, resulting in rolling movement.

1.4 Yawing movement. In the process of rotation, the four motors will rotate on their own due to the resistance of air. In order to solve the influence of the rotation, it is suggested to make two of the four motors rotate in the forward direction and the other two rotate in the opposite direction, and the rotation directions of the motors of the corresponding directions are the same. The size of the rotation force is related to the rotate speed of the motor. If the rotate speeds of the four motors are the same, then the forces of the rotation will balance each other; when there are differences in the rotate speeds of the four motors, the unbalanced rotation force will cause the rotation of the quad-rotor. As shown in Figure d, when the rotate speeds of Motor 1 and Motor 3 increase, the reaction torques will be increased as well; when the rotate speeds of Motor 2 and Motor 4 decrease, the reaction torques will be reduced as well. Then the quad-rotor body will rotate around the z axis under the force of the reaction torque, go on yawing movement, and the rotation directions are contrary to the rotation directions of Motor 1 and Motor 3.

1.5 Forward and backward movement. When the quad-rotor needs to move forward, backward, leftward and rightward in the horizontal plane, the aircraft must have forces on the horizontal plane. As shown in Figure e, increase the speed of Motor 3 and reduce the speed of Motor 1 without changing the speeds of the other two motors, then the resultant forces of Motor 1 and Motor 3 will be unbalanced. With reference to Figure b, the aircraft will begin to tilt so that the pulling force generated by the rotor wing will decompose the horizontal force to make the aircraft fly forward. The backward flight is the opposite of the forward flight. (When the four axes are pitching and rolling, they will move in the horizontal direction along the x and y axes).

1.6 Tendency movement. The tendency flight is the same as the forward and backward movement, there is no need to make further explanation.

2 Kinetic Control and Optimization of the Quad-rotor

The principles described above are based on the ideal environment, but in reality, there are too many interference factors from the outside, and whether wireless interferences or weather factors will have a significant impact on the steady flight of the aircraft. Therefore, it becomes another problem to be solved currently on how to make the aircraft adjust its own stability in time.

The PID (proportion, integral, derivative) controller has been the first practical controller for a long time, and today it is still the most widely used industrial controller. The PID controller has a simple principle and does not require too many conditions when it is used, so these advantages make it the most widely used controller. Due to the superiority of PID control, it is also suitable for the stability control of multi-rotor aircraft, so we introduce the PID algorithm into the control and optimization of multi-rotor aircraft. We will mainly analyze the principle of PID and try to control the stability of the quad-rotor with a PID controller under normal flight circumstances. The principle of PID is analyzed as follows:

Steady-state characteristic: the suppression and recovery of the control system to it after comparing the output signals with errors generated with reference to the input signals.

2.1 Law of proportion P control. In the system of Proportion P control, the regulating proportional band (Kp) of the Proportion P controller can be changed to change the steady-state error: when Kp becomes larger, the steady-state error will become smaller; otherwise, the steady-state error will become larger. But if the proportional band becomes larger, the overall stability will be reduced alone with it.

$$\Delta p = K_p e \tag{1}$$

Based on the above formula, the output value Δp and the input signal e(t) of the controller are proportional, and the rate of error reduction is also proportional to Kp. If the time constant is relatively large while the multiples of hysteresis and amplification are relative small, it is suggested to choose a smaller proportion; while if the overall sensitivity is enhanced, the response speed will become faster. If the time constant relatively small, but the multiples of hysteresis and amplification are relatively large, it is necessary to use a relatively large proportional band to ensure stability. Therefore, the simple Proportion P control can not eliminate the resulting steady-state error, which requires to introduce other control systems. Thus, the advantage of Proportion P control lies in that the control time is short, but the disadvantage is that the result has residual error.

2.2 Law of integral I control. The effect Δp of Integral I control is positively proportional to the integral of Error E:

$$\Delta p = K_I \int edt \tag{2}$$

Conclusion: the output signal values of Integral I control come from two aspects, the first is the value of deviation signal, and the second important aspect is the existence time of error. The degree of change of the control output of Integral I is positively proportional to the magnitude of the error. The control action of Integral I will eventually eliminate the error and stabilize the system.

2.3 Law of differential D control.

$$\Delta p = T_D \frac{de}{dt} \tag{3}$$

The differential time TD is the decisive factor of the effect size of the Differential D, and its size affects the velocity of the differential action. The Differential D action is of no use when there is a deviation but the deviation is constant. The differential action has the ability to suppress oscillations, which can enhance the stability of the whole, reduce the degree of change of the controlled volume, and reduce the residual error.

2.4 Law of proportion-differential PD control. When Proportion P and Differential D work together, it becomes the law of proportion-differential PD control.

$$\Delta p = \Delta p_P + \Delta p_D = K_p \left(e + T_D \frac{de}{dt} \right) \tag{4}$$

The output Δp of the proportion-differential controller equals the sum of the output ΔpP of the proportional action and the output ΔPD of the differential action. Proportional Band Kp can adjust the magnitude of proportional action while Differential TD can adjust differential action.

If there is a time-lag link in the system, then the output change will always be slower than the error, so the overall stability can be enhanced only if the action time of error is suppressed in advance.

2.5 Law of proportional integral PI control. If the whole system is stable, then Proportional Integral PI controller can be added in it, which can increase the effect of steady-state control and remove the steady-state error as much as possible. The law of proportional integral control can be expressed as follows:

$$\Delta p = K_p \left(e + \frac{1}{T_I} \int edt \right) \tag{5}$$

Proportion P regulation can counteract the interference caused by Integral I regulation, and Integral I regulation can remove the error caused by Proportion P regulation. Proportion Integral PI regulation combines the advantages of two kinds of regulation.

2.6 Law of iroportional integral-differential PID control. The controller with proportion, integral and differential control actions at the same time.

$$\Delta p = \Delta p_P + \Delta p_I + \Delta p_D = K_C\left(e + \frac{1}{T_I}\int edt + T_D\frac{de}{dt}\right) \qquad (6)$$

From the above formula, we can conclude the specific effect of PID regulation to the four axes.

Stability: Proportion P and Integral I can reduce the overall stability, and Differential D improves the overall stability of the system.

Accuracy: Proportion P and Integral I can increase the overall steady-state precision, and Differential D is not required at this time

Rapidity: Proportion P and Differential D can shorten the overall reaction speed while Integral I increases the speed.

3 Control and Optimize Data Simulation

3.1 The action of proportion P. After the system appears deviation, Proportion P will be regulated immediately. The increase of Proportion P can speed up the regulation process and reduce the steady-state error. However, the proportion can not be too large, otherwise it will reduce system stability. The Action of Proportion P is shown in fig.2.

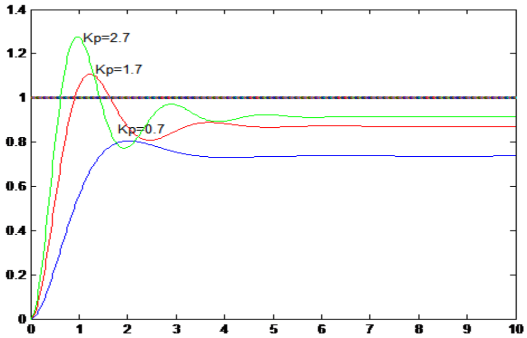

Figure 2. The Action of Proportion P

3.2 The regulating action of integral I. It will eliminate steady-state error as a whole, slow down dynamic response and decrease overall stability as well. The Regulating Action Of Integral I is shown in fig.3 and fig.4.

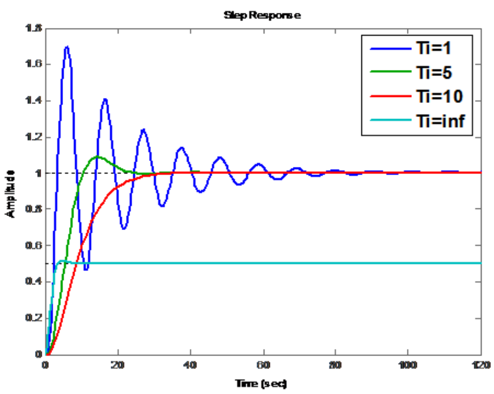

Figure 3. The Regulating Action Of Integral I (1)

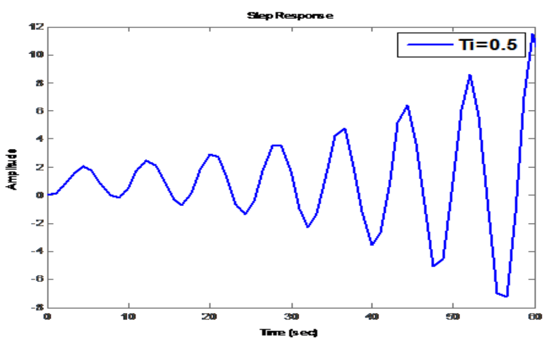

Figure 4. The Regulating Action Of Integral I (2)

3.3 The regulating action of differential D. It has function of advanced control, it is predictable and can predict the development trend of error; besides, it can improve the overall dynamic performance, reduce overshoot and decrease the regulation time. The Regulating Action Of Differential D is shown in fig.5.

3.4 The regulating action of proportional integral PI. Integral I can remove the residual error, but the speed of Integral I effect is relatively slow, and the original overall stability decreases as well. The Regulating Action Of Proportional Integral PI is shown in fig.6.

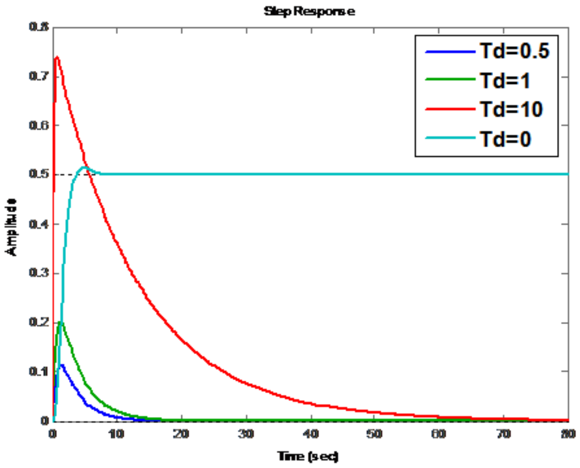

Figure 5. The Regulating Action Of Differential D

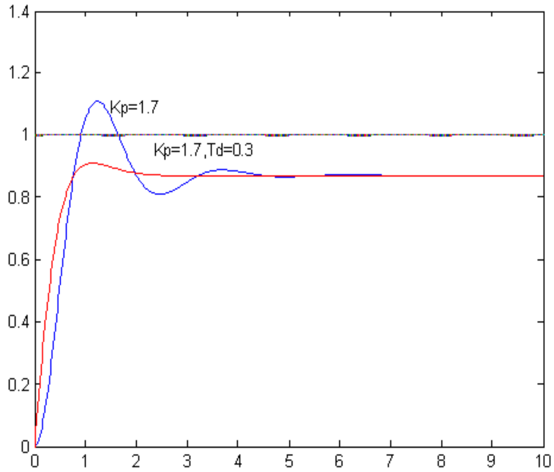

Figure 6. The Regulating Action Of Proportional Integral PI

3.5 The regulating action of proportional differential PD. Differential D has the function of restraining oscillation, which can reduce the floating degree of the controlled variable, enhance the stability of the whole, and reduce the residual error. Therefore, it is suggested to appropriately enlarge it. However, Differential D only plays an auxiliary role, and only Proportion P is the main control core. Proportional Differential PD regulation can improve the stability of the whole, but the whole system's residual error cannot be removed. The longer the action time of Differential D, the stronger its action ability, the shorter the reaction time and the more stable the whole will be as well. The Regulating Action Of Proportional Differential PD is shown in fig.7.

3.6 Regulation of proportional integral differential PID. The advantages of Proportion P, Integral I and Differential D are combined, and stability, response speed or accuracy can all obtain the ideal situation. Regulation Of Proportional Integral Differential PID is shown in fig.8.

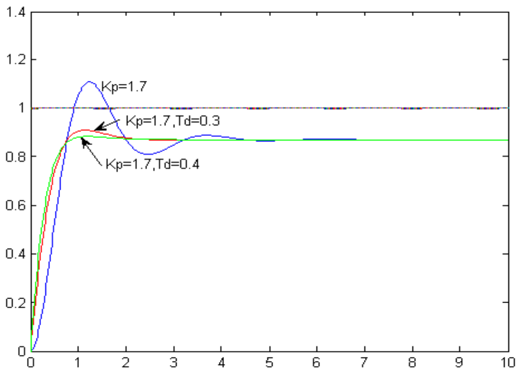

Figure 7. The Regulating Action Of Proportional Differential PD

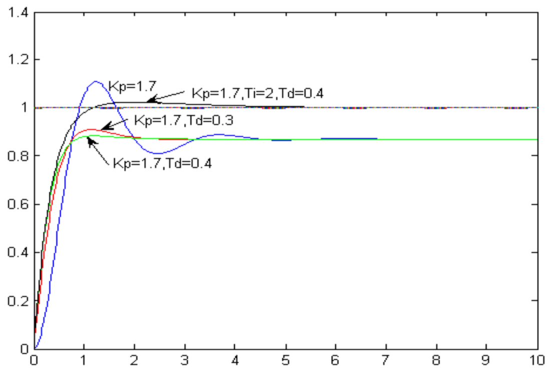

Figure 8. Regulation Of Proportional Integral Differential PID

4 Conclusion

In the regulation, the significance of P lies in the degree of error correction, and if it is too large, it will result in that the whole is balanced, but it will continue to shake violently; if it is too small, it will lead to that the degree of correction is insufficient, so P needs to be debugged to a slightly medium value patiently until the system does not have a drastic oscillation. Then it comes to I, as I is used to eliminate static error and oscillation of the body, we can first give a relatively large value, then slowly reduce it. When the oscillation of the body is mostly eliminated, it suggests that the basic adjustment of I is suitable. The last is D, since the role of D is equivalent to inhibit the overall adjustment, so it must be adjusted according to different actual conditions. But all the purposes are the same: if adjusting to the body can quickly restore the stable state without oscillations, it indicates that the basic adjustment has already been stable.

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