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Controller design for transition flight of rotor-driven VTOL fixed-wing UAV based on PID

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Abstract. The field of drones has received a lot of attention in recent years and is developing well. In the process of resource circulation in cities, UAVs play an increasingly important role, such as logistics, monitoring, emergency rescue, etc. However, traditional rotary-wing UAVs and fixed-wing UAVs can be limited in some conditions, such as load, cruising speed and take-off area. Based on the above reasons, this paper designs a rotor-driven VTOL fixed-wing UAV, which combines the vertical take-off and landing of rotor and the fast cruise of fixed-wing UAV and other characteristics. And based on this UAV, for the transition process from hovering state to cruising state, a PID controller is used to control the cruising speed, and then the flight altitude is controlled by a series-level PID controller. The final results show that the cruise speed can be stabilized at about 50km/h within 3 seconds by adjusting the PID parameters without considering the motor speed saturation. In addition, while ensuring the cruise speed reaches convergence quickly, the PID parameters of the acceleration loop, velocity loop and altitude loop can be adjusted separately to control the altitude error of the UAV within 5cm. This study provides a reference for researchers to study the control of rotor-driven UAVs in the transition process.

Keywords: PID, rotor-driven VTOL fixed-wing UAV, transition process, cruise speed control, altitude control.

1. Introduction

In recent years, the field of UAVs is developing rapidly, and they are making great achievements. Among them, vertical take-off and landing (VTOL) fixed-wing UAVs are one of the important research objects. In terms of structure, VTOL fixed-wing UAVs combine the characteristics of rotary-wing UAVs and fixed-wing UAVs. In terms of function, VTOL fixed-wing UAVs combine the vertical take-off and landing and hovering flight of rotary-wing UAVs and the high-speed flight and long-endurance flight of fixed-wing UAV. Based on these advantages, VTOL fixed-wing UAVs can perform a wider range of missions [1].

VTOL fixed-wing UAVs can be broadly classified into these categories: tilt-rotor, tilt-wing, rotor-driven, etc. [2]. Among these types of VTOL fixed-wing UAVs, rotor-driven VTOL fixed-wing UAVs are widely used in the process of resource circulation in cities, such as logistics [3], detection [4], emergency rescue [5], etc. Rotor-driven VTOL fixed-wing UAVs are driven only by the rotor wings for takeoff, landing and cruising while the fixed wings as the assistance. This structure allows the UAV to control the cruise speed, altitude and attitude of the UAV only by controlling the rotor speed and torque.

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In the flight control design of VTOL fixed-wing UAV, the main concern is for the control of vertical takeoff and landing, cruise flight and transition phase [6]. However, in terms of modelling, control and simulation, due to complex aerodynamic characteristics of the fixed wing and the distribution of the rotor wings, as well as the specificity of the transition phase from takeoff and landing to cruise, the VTOL fixed-wing UAV has a high degree of nonlinearity in its dynamics model. These problems pose a considerable challenge to the design of control systems for horizontal flight, vertical takeoff and landing, and transition processes of the aircraft [2].

Nowadays, the mainstream type of VTOL fixed-wing UAVs are tilt-rotor UAVs. Because this type of UAVs is widely used in the military field. And among many control methods, the more common ones are PID control, LQR control, etc. So, some of the controller design methods used on tilt-rotor UAVs are listed, such as PID, LQR, MPC, SMC, etc. Then, we compare PID, LQR, MPC, and SMC controllers.

This paper is mainly divided into the following parts. The second part briefly introduces some control methods, such as PID, LQR, MPC, SMC, etc., and lists the applications of some control methods on tilt-rotor UAVs that are popular at this stage. The third part unfolds the simulation platform and model. The fourth part describes in detail the algorithms of single PID controller and string-level PID controller. The fifth part describes the experimental steps and gives the simulation model. The sixth part discusses the experimental results after parameter tuning. The last part clarifies the conclusions drawn from this experiment and the problems that exist.

2. Related works

The PID algorithm is shown in figure 1. The biggest advantage of PID controller is that it can achieve the optimal control effect through relatively accurate parameter adjustment, and it can control without getting the system model. However, once multiple targets are controlled, the parameter adjustment workload is larger [7].

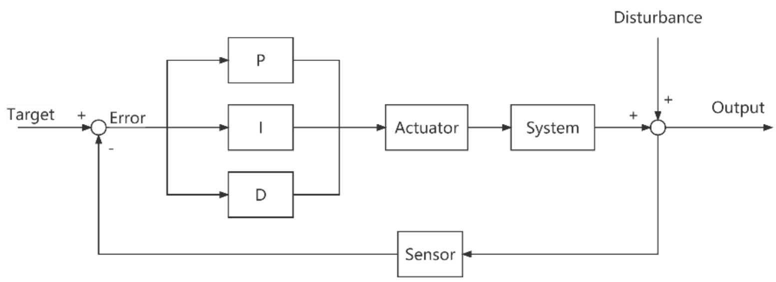

Figure 1. PID algorithm.

The LQR algorithm is shown in figure 2. The advantage of the LQR controller is that it can control multiple objectives with a single parameter adjustment [8]. However, the disadvantage is that after linearizing the system model, only the local optimal solution can be solved. Moreover, LQR control requires knowledge of the system model.

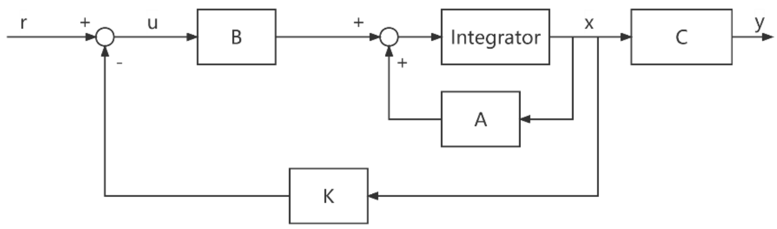

Figure 2. LQR algorithm.

However, PID controllers and LQR controllers can have constraints in some situations, such as motor saturation, resulting in the controller's control not being as effective as expected [9].

The MPC algorithm is shown in figure 3. The advantage of MPC is that it is possible to achieve multiple inputs and outputs with only one controller. The disadvantage is the need to design an observer when the state quantity is unknown, which is troublesome [8].

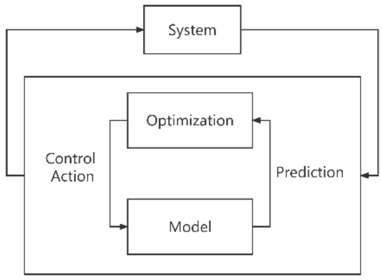

Figure 3. MPC control thought.

The SMC algorithm is a novel control algorithm which has been used in many fields. One of the major advantages of SMC is that it is artificially parameterized, highly robust to external disturbances, and does not require knowledge of the system model [10]. The disadvantage is that it tends to jitter back and forth at the equilibrium point of control and fails to converge.

Most researchers tend to use the PID controller. For example, Yu et al. [11] designed a PID cascade controller, which consists of an inner loop that uses a PI controller to control the attitude and an outer loop that uses a PID controller to control the height. Besides, Nakamura et al. [12] designed four PD controllers to control the altitude and three attitude angles.

Other control methods like LQR and SMC are also used. For example, Chen et al. [13] used PEM (Prediction Error Minimization) to identify the tilt-rotor UAV system and then controlled the attitude angles by the outer loop PID controller, while the inner loop used the LQR controller to control the three angular velocities. Then, since the SMC method is excellent for noise suppression and model inaccuracy handling, Sridhar et al. [14] used the SMC method to design the controller to control the tilt-rotor UAV system.

3. Methodology

3.1. Platform and model

In this study, MATLAB and Simulink are used as the experimental platform for modelling and simulation, and tune the PID controller parameters. For the rotor-driven VTOL fixed-wing UAV, it can be assumed that the centre of lift of the fixed wing, the centre of lift of the four vertical rotors, and the centre of gravity are at the same point, and that the active line of thrust generated by the tail rotor acts through this point. For the translational motion of the UAV, the kinematic equations are following:

$$\dot{x} = v_x \quad \dot{y} = v_y \quad \dot{z} = v_z \tag{1}$$

Since the earth coordinate system is different from the body coordinate system, the transformation matrix from the body coordinate system to the earth coordinate system is:

$$R = \begin{bmatrix} c\theta c\psi & c\psi s\theta s\varphi - s\psi c\varphi & c\psi s\theta c\varphi + s\psi s\varphi \\ c\theta s\psi & s\psi s\theta s\varphi + c\psi c\varphi & s\psi s\theta c\varphi - c\psi s\varphi \\ -s\theta & s\varphi c\theta & c\varphi c\theta \end{bmatrix} \tag{2}$$

where $c\theta$ represents $\cos\theta$, and $s\theta$ represents $\sin\theta$. This regulation is the same to ψ and φ. Therefore, the dynamic equations of the translational motion are following:

$$m\begin{bmatrix} \dot{v_x} \\ \dot{v_y} \\ \dot{v_z} \end{bmatrix} = m\begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix} + R * \begin{bmatrix} T_t - f \\ 0 \\ F_{fwt} + F_{rwt} \end{bmatrix} \tag{3}$$

where g is the acceleration of gravity, T_t is the thrust of the tail rotor, f is the air resistance of the fixed wing, F_{fwt} is the lift generated by the fixed wing, and F_{rwt} is the sum of the lift generated by the rotor. The equations for F_{fwt} and f are following:

$$\begin{gathered} F_{fwt} = 0.5C_p\rho S v_t^2 \\ f = 0.5C_d\rho S v_t^2 \\ m\dot{v}_t = T_t - f - mgsin\theta \end{gathered} \tag{4}$$

where C_p is the lift coefficient, C_d is the air drag coefficient, ρ is the atmospheric density, S is the area of the upper surface of the fixed wings, and v_t is the velocity along the fuselage direction. Then the mathematical model is put into Simulink, and is set three attitude angles to zero, as shown in figure 4.

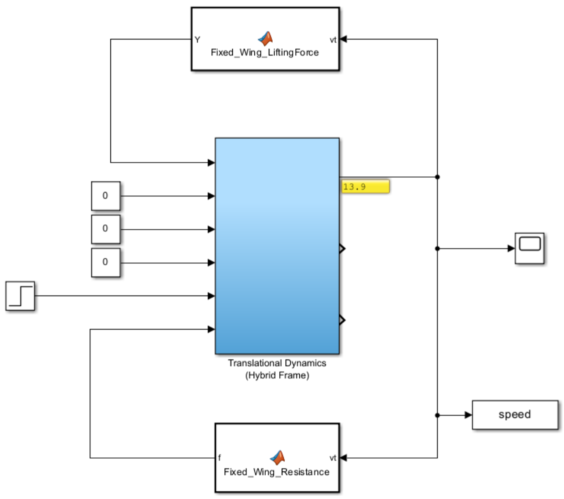

Figure 4. The rotor-driven VTOL fixed-wing control model.

3.2. *Control algorithm*

According to a large number of studies, the LQR control method has great advantages for many nonlinear systems, but the use of LQR controllers require known systems. For unknown systems, identifying the system by linear fitting method will have large errors, so the LQR method control is not accurate enough. In contrast, the PID method has more considerable generalizability for the control of nonlinear systems. In addition, control methods such as SMC, MPC, etc. are only used for applications requiring high accuracy due to their more complex mathematical models and parameter adjustment methods. Therefore, this experiment designs two controllers to control the transition process of rotor type VTOL fixed-wing UAV, which are the cascaded PID controller controls the height, the single PID controller controls the speed, and then the system is stabilized by parameter adjustment.

In this study, the single PID control algorithm is formulated as follows:

$$u(t) = K_p * e(t) + K_i * \int_0^t e(\tau)d\tau + K_d * \frac{de(t)}{dt} \tag{5}$$

where $u(t)$ is the output quantity, $e(t)$ is the error value, K_p is the proportionality factor, K_i is the integration factor, and K_d is the differentiation factor.

In general, the proportionality factor K_p amplifies the error value, allowing the system to converge to the steady state faster. However, with too large K_p, this system is prone to overshoot and even divergence. Adjusting the integration factor K_i allows the processed system input to allow the system to break through a certain threshold, avoiding steady-state errors caused by zero output in a certain input range. And the differential term K_d, which can predict the direction of the error. The introduction of the differential term can effectively reduce the overshoot. However, the differential term reduces the rate of change of the system output, which leads to a slightly longer steady-state time. Therefore, reasonable adjustment of the three parameters that K_p, K_i and K_d, is generally effective in designing a PID controller that makes the control system respond quickly, with small overshoot and zero error.

The cascaded PID controller is a series of PID controllers that control different physical quantities in series, and there are some corresponding relationships between these physical quantities. In general, the innermost PID parameters are adjusted before the outer PID parameters are adjusted.

Then the mainly work is tunning the parameters K_p, K_i and K_d of these PID controllers to design the PID controller.

3.3. Experimental procedure

In this study, all three attitude angles are set to 0, and then a single PID controller is designed to control the speed of the drone's fixed speed cruise. Next, a cascaded PID controller is used to maintain a stability of height, as shown in figure 5. Then the innermost loop which represents acceleration loop is adjusted first, followed by the second inner loop which represents velocity loop, and eventually the outer loop which represents height loop.

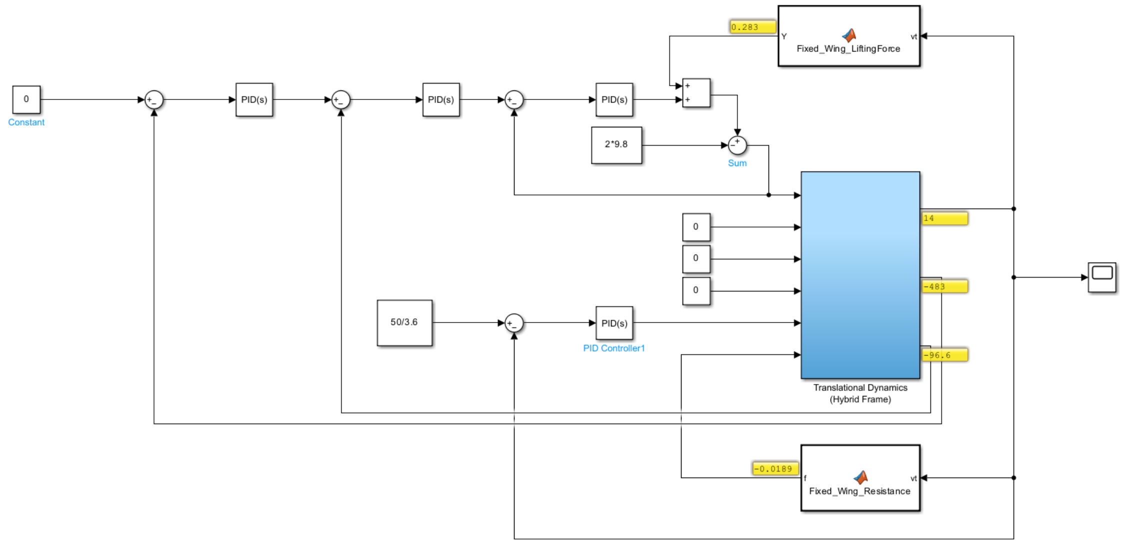

Figure 5. The cruise speed control and height control model.

4. Experimental results and analysis

The constant speed is set to 50 km/h and the PID parameters are adjusted to K_p = 20, K_i = 5, K_d = 5. The output is shown in figure 6.a). By adjusting the parameters, the tail motor can increase the speed of the aircraft to 50km/h which is equal to 13.9 m/s, and keep it stable within one second. Then the acceleration loop parameters are set to K_p = 40, K_i = 5, K_d = 15, and the output is shown in figure 6.b). The acceleration is within 0.5m/s^2, and the change in velocity and height is also small. After that, the velocity loop parameters are set to K_p = 35, K_i = 3, K_d = 10, and the output is shown in figure 6.c). Eventually, the height loop parameters are set to K_p = 10, K_i = 3, K_d = 5, and the result is shown in figure 6.d). After switching to cruise mode, the altitude of the drone is stable within 5cm, which is within the allowable error range, and then makes the transition process smooth.

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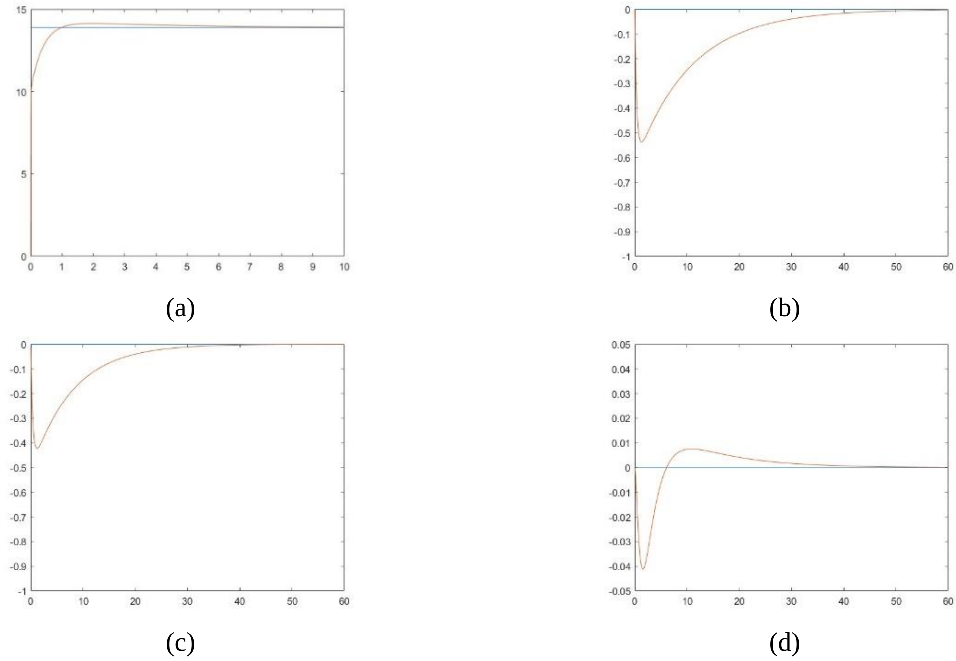

Figure 6. Time history of kinematic parameters. (a) is cruise speed; (b) is acceleration of z-axis; (c) is velocity of z-axis; (d) is altitude change.

5. Conclusion

In this study, the dynamics of the rotor-driven VTOL fixed-wing UAV is modelled, and then the transition process from hovering to cruising is controlled in two steps based on PID controller. The first step is to control the tail rotor for the determined cruise speed, and the second step is to control the stability of the flight altitude during the transition process by adjusting the three closed loops of acceleration, velocity and altitude respectively, which has high robustness. Final experimental results show that the cruise speed can be stabilized at about 50 km/h within 3 seconds by adjusting the PID parameters without considering the motor speed saturation. After the cruise speed is converged, the height can be controlled within 5 cm smoothly by adjusting the parameters of three PID controllers. This study can provide ideas and design guidelines for the design of transition process controllers for rotor-driven VTOL fixed-wing UAVs.

During the study, the number of parameters to be adjusted in the process of controlling multiple variables using PID controllers is too large. Moreover, in practical engineering scenarios, control systems are often not time-invariant systems. Therefore, the author believes that in practical engineering applications, a PID controller with fixed parameters is not the optimal choice. In case of practical requirements for accuracy, machine learning can be used to dynamically adjust the parameters, or to reduce the controllers' parameters to be adjusted such as LQR, or to design controllers by higher accuracy models such as MPC, SMC, etc.

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