Position and Attitude Tracking Control for a Quadrotor UAV via Double-loop Controller

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Abstract: To deal with the position and attitude tracking control problem of a quadrotor unmanned aerial vehicle (UAV), the proportional-derivative (PD) and integral sliding mode techniques are adapted to design a double-loop controller in this paper. Firstly, the system model of quadrotor is established according to the Lagrange formalism. Then, a PD control method is put forward in the outer-loop to achieve the position tracking. Meanwhile, an integral sliding mode control method is adapted in the inner-loop to ensure the quadrotor track the desired attitude angles in the presence of external disturbances. Accordingly, a double-loop controller is generated. Finally, simulation results are presented to verify the effectiveness and robustness of the proposed control laws.

Key Words: quadrotor, PD control, integral sliding mode control, double-loop controller, tracking

1 INTRODUCTION

Quadrotor, as a kind of vertical take-off and landing (VTOL) aircraft, has received extensive attention in the past few years. Featured with simple mechanical structure, low cost, small size and flexible maneuverability [1, 2], the quadrotor has been widely used in surveillance, search and rescue, environmental monitoring, information collection and many other situations [3].

In applications, the quadrotor suffers from various control difficulties [4]. Firstly, the dynamic model of the quadrotor has six-degree-of-freedom (DOF) with only four independent thrust forces generated by four rotors [5], which is regarded as an under-actuated system [6]. It is not possible to control all of the states directly and simultaneously [7]. Secondly, the quadrotor is known as a multi-variable, nonlinear, strong coupled system [8]. Thirdly, the quadrotor usually operates in the presence of external disturbances such as wind gusts, sideslip aerodynamics and payload internal friction [9]. Thus, the quadrotor requires not only a fast response hardware but also high performance of control algorithms.

For the sake of performing automatic flight, different control strategies have been proposed for the quadrotor [10]. The linear control methods such as proportional-integral-differential (PID) control and linear-quadratic regulator were presented in [11, 12]. For these linear control techniques, it is observed that the convergence can not be guaranteed when the quadrotor moves away from its flight domain [13]. For instance, PID control algorithm were adapted to realize the tracking control of quadrotor in [14], but it reduced the steady state error by increasing the controller gain, and the system was easily affected by external disturbance [15]. Moreover, since the nonlinear control methods can overcome limitations and drawbacks of linear approaches by substantially expanding the domain of controllable flights [16], a variety of nonlinear flight control methods have been developed, such as backstepping control [17], fuzzy control [18], adaptive control [19] and sliding mode variable structure control [20].

In this paper, a double-loop controller is developed to solve the tracking control problems of quadrotors. Firstly, a PD control method [21] is chosen to control the outer-loop subsystem. Then, an integral sliding mode [22] controller is designed to control the inner-loop subsystem due to its robustness against disturbances and parameter uncertainties. Furthermore, the boundary layer solution [23] is employed to eliminate the chattering phenomenon [24].

The rest of this paper is organized as follows: Section 2 presents the system model of quadrotor via a Lagrange approach. A double-loop control configuration is presented to deal with the difficulty of the controller design in Section 3. Simulation results are provided to demonstrate the effectiveness and robustness of the proposed methods in Section 4. Finally, Section 5 gives a brief conclusion of the proposed control algorithm.

2 THE SYSTEM MODEL OF QUADROTOR

In this section, the system model is established to control the quadrotor accurately. As is shown in Fig. 1, a quadrotor conventional structure is composed of four rotors, which

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can increase the mobility and loadability. The motion of the quadrotor is controlled by adjusting the rotation speed of four rotors to change the thrust and the torque produced by each one. In order to eliminate the anti-torque, the quadrotor system is divided into two opposite rotor pairs(rotor 1, 3 and rotor 2, 4) where one pair rotates clockwise while the other pair counters clockwise. There are three common movements of the quadrotor. Pitch movement is obtained by increasing (reducing) the speed of the rear motor while reducing (increasing) the speed of the front motor. The roll movement is produced similarly using the lateral motors. The yaw movement is obtained by increasing (decreasing) the speed of the front and rear motors while decreasing (increasing) the speed of the lateral motors [25].
In order to describe the quadrotor's flight information, the following two frames should be built up, let $E = [X_E, Y_E, Z_E]$ be the inertial frame and $B = [X_b, Y_b, Z_b]$ denote the frame attached to the quadrotor as described in Fig. 1.

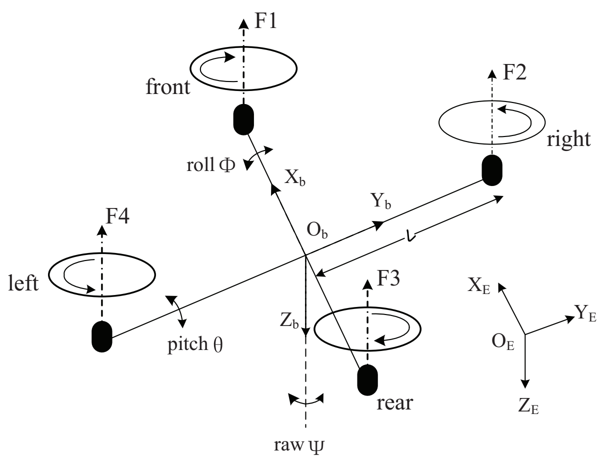

Figure 1: Configuration of the quadrotor

The system model of quadrotor can be obtained via a Lagrange approach, a simplified model is given as follow [26]:

$$\left\{\begin{array}{l} \ddot{x} = u_1(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) - K_1\dot{x}/m \\ \ddot{y} = u_1(\sin\phi\sin\theta\cos\psi - \sin\phi\cos\psi) - K_2\dot{y}/m \\ \ddot{z} = u_1(\cos\phi\cos\psi) - g - K_3\dot{z}/m \\ \ddot{\phi} = u_2 - lK_4\dot{\phi}/I_1 \\ \ddot{\theta} = u_3 - lK_5\dot{\theta}/I_2 \\ \ddot{\psi} = u_4 - K_6\dot{\psi}/I_3 \end{array}\right. \tag{1}$$

where:

- (x, y, z) denote the position of quadrotor in the earth-frame
- (ϕ, θ, ψ) describe the orientation of quadrotor *i.e.* pitch, roll, yaw angles respectively.
- m is the total mass of the structure
- g is the acceleration of gravity
- l is the lever length
- $K_i(i = 1, ..., 6)$ are the drag coefficients
- $I_i(i = 1, ..., 6)$ are the moments of inertia with respect to the axes
- u_i are the inputs terms defined as follow

$$\left\{\begin{array}{l} u_1 = (F_1 + F_2 + F_3 + F_4)/m \\ u_2 = l(-F_1 - F_2 + F_3 + F_4)/I_1 \\ u_3 = l(-F_1 + F_2 + F_3 - F_4)/I_2 \\ u_4 = c(F_1 - F_2 + F_3 - F_4)/I_3 \end{array}\right. \tag{2}$$

where F_i are thrusts generated by four rotors and can be considered as the real control inputs to the system, and c is a force to moment scaling factor.

3 DESIGN OF CONTROLLER

The overall objective of the control algorithm developed in this paper is to track a desired trajectory $\xi_d = (x_d, y_d, z_d)^T$ and a desired yaw angle ψ_d. It is worthwhile to note from the quadrotor system that the angles and their time derivatives do not depend on translation components. Moreover, the translation components depend on the angles. Normally, the overall system described by formula (1) can be regarded as constituted of two subsystems: the linear translation and the angular rotations. Two controllers can be designed for the two subsystems, respectively. In translational subsystem, a PD controller is designed to calculate the control law u_1 and the desired posture of the quadrotor (ϕ_d, θ_d), which ensures the quadrotor track the desired trajectory ξ_d. Accordingly, desired angles $\eta_d = (\phi_d, \theta_d, \psi_d)^T$ are derived. In rotational subsystem, an integral sliding mode controller is designed to obtain control laws u_2, u_3 and u_4, which ensures the quadrotor track the desired attitude angles in the presence of external disturbances, and the integral item helps to guarantee system's stability and zero errors under disturbances. The overall control strategy is illustrated in Fig. 2.

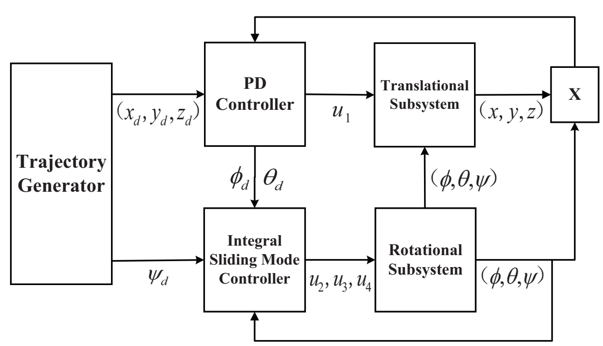

Figure 2: Synoptic scheme of the proposed control strategy

3.1 Design of Position Controller

The goal of this subsection is to design a tracking control scheme for the translational subsystem, which ensures the tracking error converge to zero asymptotically.

To begin, define new control inputs u_{1x}, u_{1y} and u_{1z}, satisfying:

$$\begin{cases} u_{1x} = u_1(\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi) \\ u_{1y} = u_1(\sin\phi\sin\theta\cos\psi - \sin\phi\cos\psi) \\ u_{1z} = u_1\cos\phi\cos\psi \end{cases} \tag{3}$$

Then the equation of translational subsystem can be rewritten as follows:

$$\begin{cases} \ddot{x} = u_{1x} - K_1\dot{x}/m \\ \ddot{y} = u_{1y} - K_2\dot{y}/m \\ \ddot{z} = u_{1z} - g - K_3\dot{z}/m \end{cases} \tag{4}$$

The desired control inputs for X, Y and Z are given by

$$\begin{cases} u_{1x} = -k_{px}x_e - k_{dx}\dot{x}_e \\ u_{1y} = -k_{py}y_e - k_{dy}\dot{y}_e \\ u_{1z} = -k_{pz}z_e - k_{dz}\dot{z}_e + g \end{cases} \tag{5}$$

where $x_e = x - x_d$, $y_e = y - y_d$, $z_e = z - z_d$, k_{px}, k_{py} , k_{pz} are the proportional gains of the PD controller, and k_{dx}, k_{dy}, k_{dz} are the differential gains of the PD controller. Furthermore, from (3), two desired attitude angles which will be employed as desired trajectory in rotational subsystem can be received, that is

$$\begin{cases} \phi_d = arctan(\frac{\sin\psi\cos\psi u_{1x} - \cos^2\psi u_{1y}}{u_{1z}}) \\ \theta_d = arcsin(\frac{\cos^2\psi u_{1x} + \sin\psi\cos\psi u_{1y}}{u_{1z}}) \end{cases} \tag{6}$$

From the desired roll angle ϕ_d, the control input u_1 can be easily given as

$$u_1 = \frac{u_{1z}}{cos\phi_d cos\psi} \tag{7}$$

Theorem 1.
Under the control input described by formula (5), the globally tracking angles ϕ_d and θ_d can be guaranteed.
Proof.
According to (5), it easy to find that $u_{1x} = u_{1y} = 0$ when the position angle errors converge to zero.
Substitute $u_{1x} = u_{1y} = 0$ into (6), it can be obtained that $\phi_d = \theta_d = 0$.
Therefore, under the control input for X, Y and Z, two desired attitude angles will converge to zero.

3.2 Design of Attitude Controller

Attitude control is the key of the quadrotor control and its control performance will greatly affect the flight stability [27]. In this subsection, an integral sliding mode controller is adopted to track the desired attitude angles in rotational subsystem. In traditional sliding mode control, it is hard to guarantee zero errors under disturbances. Thus, the integral sliding mode control is introduced as attitude control method to solve the above problem. According to the decoupled linear model, the pitch channel, roll channel and yaw channel integral sliding mode controllers can be designed independently.
For traditional sliding mode control, first stage of design control is to define the sliding surface function. Let the sliding surface function be defined as:

$$S = \dot{e} + K_p e \tag{8}$$

where $K_p \in R^+$, e is the tracking error.
The sliding mode control with integral action scheme introduces a *sliding surface* along which the sliding motion is to take place. This surface is denoted by S and is defined as follow:

$$S = \dot{e} + K_p e + K_I \int_0^t e\, d\tau \tag{9}$$

As for the control of roll angle, its dynamic equation is:

$$\ddot{\phi} = u_2 - lK_4\dot{\phi}/I_1 \tag{10}$$

Let the desired roll angle be ϕ_d, and define the error as $e = \phi - \phi_d$. Thus, the integral sliding mode surface will be:

$$S = \dot{\phi} - \dot{\phi}_d + k_1 e + \int_0^t (k_2 e)\, d\tau \tag{11}$$

where k_1 is the slope of the sliding line and k_2 is the integral gain. The derivative of the sliding surface can be given as:

$$\dot{S} = \ddot{\phi} - \ddot{\phi}_d + k_1\dot{e} + k_2 e \tag{12}$$

Choose the following exponential reaching law:

$$\dot{S} = -Msgn(S) - kS \tag{13}$$

where M and k are positive constants, and $sgn(\cdot)$ denotes the signum function.
From (10), (12) and (13), it easy to show that:

$$\begin{aligned} u_2 = {} & lK_4\dot{\phi}/I_1 + \ddot{\phi}_d - Msgn(S) - kS \\ & - k_1(\dot{\phi} - \dot{\phi}_d) - k_2(\phi - \phi_d) \end{aligned} \tag{14}$$

Theorem 2.
Considering the system model of quadrotor described by formula (1), the flight controller of roll angle is designed as (14). Under the integral sliding mode controller, the nonlinear system is stable.
Proof.
Consider the following Lyapunov function candidate:

$$V = \frac{1}{2}S^2 \tag{15}$$

Differentiating (15) with respect to time and using (13), it can be obtained that:

$$\begin{aligned} \dot{V} &= S\dot{S} \\ &= S(-Msgn(S) - kS) \\ &= -Msgn(S)\cdot S - kS^2 \le 0 \end{aligned}$$

Therefore, the Lyapunov equation $\dot{V} \le 0$ can ensure that attitude angle errors will converge to zero along with the desired integral sliding mode surface.
Similarly, for state θ and ψ, integral sliding mode controllers are designed to ensure θ and ψ converge to its desired value θ_d and ψ_d. The control input u_3 and u_4 are designed as follows:

$$\begin{aligned} u_3 = {} & lK_5\dot{\theta}/I_2 + \ddot{\theta}_d - M_\theta sgn(S) - k_\theta S \\ & - k_{1\theta}(\dot{\theta} - \dot{\theta}_d) - k_{2\theta}(\theta - \theta_d) \end{aligned} \tag{16}$$

$$u_4 = K_6\dot{\psi}/I_3 + \ddot{\psi}_d - M_\psi sgn(S) - k_\psi S - k_{1\psi}(\dot{\psi} - \dot{\psi}_d) - k_{2\psi}(\psi - \psi_d) \tag{17}$$

where M_θ, k_θ, $k_{1\theta}$, $k_{2\theta}$, M_ψ, k_ψ, $k_{1\psi}$ and $k_{2\psi}$ are positive controller parameters to be determined later.

The main advantage of the control algorithm based on sliding mode technique is its robustness against parameter variations and external disturbances on the switching surface. Unfortunately, an ideal sliding mode controller has a discontinuous switching function and it is assumed that the control signal can be switched from one value to another infinitely fast. In practical systems, it is impossible to achieve infinitely fast switching control because of finite time delays for the control computation and limitations of physical. Due to imperfect switching in practice, it raises the issue of chattering which is highly undesirable. It appears high frequency oscillation near the desired equilibrium point and may excite the unmodelled high-frequency dynamics of the system [28].

The boundary layer method is one of the most common and effective solutions to chattering problem. Consequently, a saturation function is used to replace the sign function. The saturation is defined as follow:

$$sat(y) = \begin{cases} y & |y| \leq 1 \\ sgn(y) & |y| > 1 \end{cases} \tag{18}$$

where $y = S/\lambda$, $\lambda > 0$ and λ is the thickness of boundary layer.

The saturation function is applied to reduce the system chattering. The effect of this adjustment will be shown in the coming simulation section.

4 SIMULATION AND RESULTS ANALYSIS

In this section, several simulations are given to illustrate the effectiveness of the proposed control strategy, including the position and attitude tracking performance of quadrotor. In addition, external disturbances are considered to test stability robustness in the integral sliding mode controller.

The parameters of quadrotor used in this paper are listed in Tables 1, which represent approximate conditions found in real flying conditions in a controlled environment.

Table 1: Parameters of the quadrotor aircraft

Symbol	value	Unit
m	2	kg
g	9.8	m/s^2
l	0.2	m
I_1, I_2	1.25	$kg \cdot m^2$
I_3	2.5	$kg \cdot m^2$
K_1, K_2, K_3	0.010	Ns/m
K_4, K_5, K_6	0.012	Ns/m

In simulation experiment, the initial value of quadrotor position is $(x\ y\ z) = (0\ 0\ 0)$, the initial value of attitude angle is $(\phi\ \theta\ \psi) = (0\ 0\ 0)$, the desired value of position in fixed point flight and hovering is $(x\ y\ z) = (4\ 3\ 5)$, and the desired value of the yaw angle is $\psi_d = \frac{\pi}{4}$. External disturbances $d = 10$ is also added in the simulation.

The following controller parameters are used in simulations:

$k_{px} = k_{py} = 1.8$, $k_{dx} = k_{dy} = 2.5$, $k_{pz} = 5.5$, $k_{dz} = 4.5$, $M = M_\theta = M_\psi = 25$, $k = k_\theta = k_\psi = 1$, $k_1 = 5.5$, $k_2 = 10$, $k_{1\theta} = 5.5$, $k_{2\theta} = 40$, $k_{1\psi} = 8.5$, $k_{2\psi} = 20$.

The simulation results are shown in Fig. 3, Fig. 4, Fig. 5 and Fig. 6.

Fig. 3 and Fig. 4 show the position and attitude tracking behavior of the quadrotor, as desired, x, y, z, ψ can converge to its desired value x_d, y_d, z_d, ψ_d. It can be noted that the tracking errors will converge to zero when all states asymptotically converge to their desired values. This demonstrates the effectiveness of the double-loop control scheme.

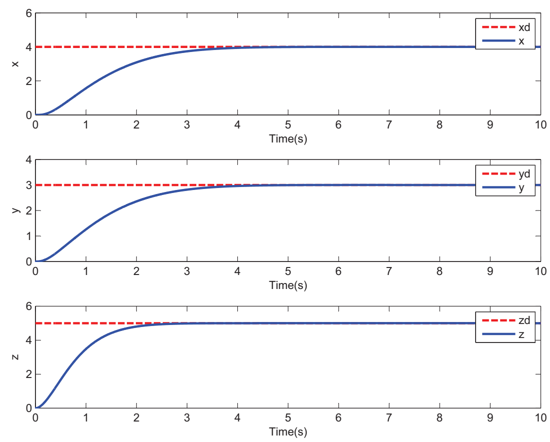

Figure 3: position tracking behavior of the quadrotor

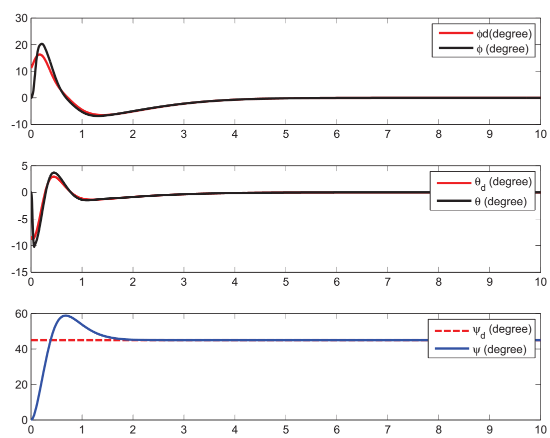

Figure 4: attitude tracking behavior of the quadrotor with the integral sliding mode control

The results of the simulation based on the integral sliding mode control and traditional sliding mode control with external disturbances are shown in Fig. 4 and Fig. 5. As we can see in Fig. 5, the angle values can not converge to their desired values and tracking errors will not converge to zero. It can be concluded that the sliding mode control with integral action scheme can guarantee zero errors under disturbances.

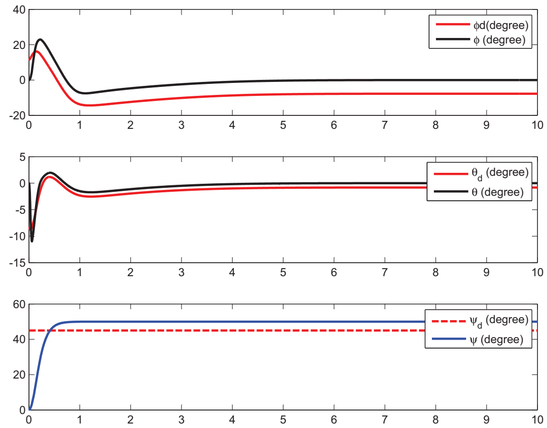

Figure 5: attitude tracking behavior of the quadrotor wit the sliding mode control

As we can see in Fig. 6 and Fig. 7, if we take no action to eliminate the chattering phenomenon, control laws u_2, u_3, u_4 appear high frequency oscillation near the desired equilibrium point, which is difficult to realize in practical control. It can be concluded that the boundary layer method is effective to reduce the chattering phenomenon.

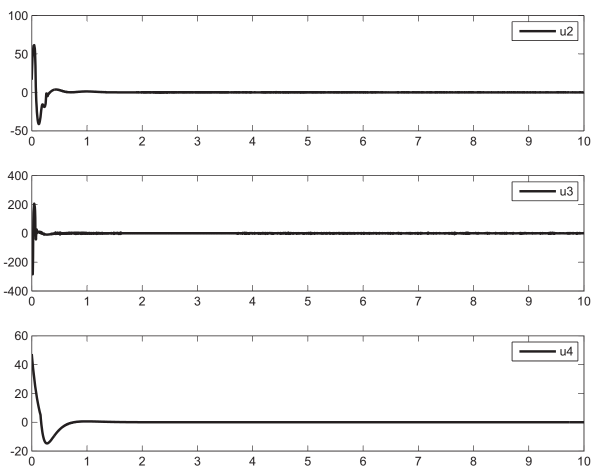

Figure 6: control laws u_2, u_3, u_4 with boundary layer method

5 CONCLUSION

Considering a quadrotor subjected to external disturbances, a double-loop controller was proposed to bring the quadrotor to a stable hovering position. Simulation results showed that the sliding mode control with integral action scheme is able to eliminate the steady-state error. Moreover, the control strategy proposed in this paper has strong robustness. Beside this, the proposed controller can also move the quadrotor to a desired position with a desired yaw angle while keeping the pitch and the roll angles zero.

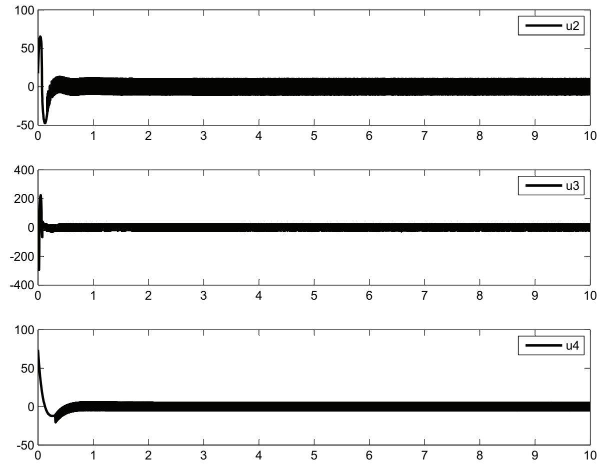

Figure 7: control laws u_2, u_3, u_4 with no method to reduce the chattering

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