Research on a Robust Backstepping Attitude Controller for Multi-rotor Plant Protection UAV

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Abstract. The plant protection UAV is an important application equipment for precision spraying technology. However, in the process of spraying, the change of its own load will lead to the decline of control performance and disturbance rejection ability. In order to improve the control performance of the plant protection UAV, the application research of robust backstepping control strategy is carried out, and the Robust Backstepping Attitude Controller (RBAC) is designed to force the quadrotor to follow the desired attitude. Through simulation experiments, the control effect of RBAC and the Backstepping Terminal Sliding Mode Controller (BTSMC) in the literature are compared and analysed. The simulation results show that: RBAC can improve the dynamic performance of the system. The average settling time of the system is shortened by 404.663ms, which is 24.85% faster than that of the BTSMC system. Simultaneously, the system is insensitive to external unknown disturbance and has strong robustness.

Keywords: Attitude Controller, Nonlinear Control, Plant Protection UAV, Robust Backstepping Control

1. Introduction

Nowadays, the multi-rotor UAV has been widely used in many fields. Since it is an underactuated system which is multivariate and highly coupled[1], and there are various external disturbances in the practical application, the design of UAV controllers remains a challenging task[2]. Therefore, many control methods, such as PID control, backstepping control, robust control, etc.[3-5], have been studied to perform the stable control of the quadrotor. The plant protection UAV needs to keep its attitude stable during the spraying operation[6, 7], but the dynamic parameters of the fuselage will change with the gradual decrease of the liquid[8, 9], which may degrade the control performance and the disturbance rejection ability[10]. So, it is necessary to design a new controller to improve the dynamic performance of the plant protection UAV system.

At present, in the flight control researches of the multirotor plant protection UAV, only a few take the load mass change problem as the research object[11, 12]. Liu et al.[13] designed a fuzzy PID controller, which performed better than the PID controller. But when the multi-rotor plant protection UAV was chosen as the controlled plant, the performance had obvious overshoot, and the settling time
was more than 1000ms. Wang et al.[12] proposed BTSMC which has obvious effect improvement compared with the fuzzy PID control method. However, there is still room for optimization.

Based on the time-varying dynamic model of the multi-rotor plant protection UAV, we analyze and establish the model of the liquid tank, and adopt the robust backstepping control strategy for nonlinear time-varying system to design a robust backstepping controller for the attitude control. The selection basis of controller parameters is analyzed simultaneously. Then the RBAC is compared with the BTSMC to prove the superiority of RBAC.

2. System Modeling

The dynamic model of the multi-rotor plant protection UAV can be expressed as

\[
\begin{align*}
\dot{x} &= \frac{1}{m_i} (\cos \phi \sin \theta \cos \psi + \sin \phi \sin \psi)u_z - \frac{K_1 \dot{x}}{m_i} \\
\dot{y} &= \frac{1}{m_i} (\cos \phi \sin \theta \sin \psi - \sin \phi \cos \psi)u_z - \frac{K_2 \dot{y}}{m_i} \\
\dot{z} &= \frac{1}{m_i} (\cos \phi \cos \theta)u_z - g - \frac{K_3 \dot{z}}{m_i} \\
\dot{\phi} &= \hat{\phi} - \frac{I_y - I_z}{I_x} \dot{\psi} + \frac{J}{I_x} \Omega_\phi + \frac{1}{I_x} u_\phi \\
\dot{\theta} &= \hat{\theta} - \frac{I_z - I_x}{I_y} \dot{\psi} + \frac{J}{I_y} \Omega_\theta + \frac{1}{I_y} u_\theta \\
\dot{\psi} &= \hat{\psi} - \frac{I_x - I_z}{I_z} \dot{\phi} + \frac{1}{I_z} u_\psi
\end{align*}
\]  

(1)

where \(x, y, \) and \(z\) are spatial coordinates of the ground system, \(m_i\) is the total mass of the fuselage, \(K_i\) is the air resistance coefficient, \(g\) is the gravitational acceleration, \(u_z\) is the control input, \(\phi, \theta, \) and \(\psi\) are angles of roll, pitch and yaw, respectively, \(l\) is the arm length, \(J\) is the rotational inertia of rotors, \(\Omega_i\) is the angular velocity of rotors, \(u_\phi, u_\theta,\) and \(u_\psi\) are control inputs of attitude angle channels, and \(I_x, I_y, \) and \(I_z\) are the rotational inertia of three axes.

The liquid tanks have some kinds of shapes, such as T type, U type, cuboid type, etc. These shapes of liquid tanks are designed to reduce the shaking of the pesticide in them during the spraying process, so the liquid inside them can be regarded as a solid that reduces in mass over time. For lack of space, only the T type liquid tank is discussed in this paper. The simplified model of the liquid tank is shown in Figure 1, where \(d_0 \) and \(d_1\) are the length, \(b\) is the width, \(h_0\) and \(h_1\) are the height, respectively.

Changes of the pesticide mass in the liquid tank have little effect on the position of the mass center of the UAV[12], so it can be assumed that the position of mass core of the UAV does not change over time. In order to deduce the formula of the rotational inertia of the liquid tank, the coordinate system of the simplified model of the liquid tank is established, as shown in Figure 1.

According to parallel axis theorem, define \(h\) as the height, when \(h > h_0\), the rotational inertia around three axes is calculated as follows:
\[
I_{x1} = \frac{1}{12} m_0 (a_0^2 + h_0^2) + m_0 \left( \frac{h_0}{2} + h_1 \right)^2 + \frac{1}{12} m_h [a^2 + (h - h_0)^2] + m_h \left( \frac{h - h_0}{2} \right)^2 \\
I_{y1} = \frac{1}{12} m_0 (b_0^2 + h_0^2) + m_0 \left( \frac{h_0}{2} + h_1 \right)^2 + \frac{1}{12} m_h [b^2 + (h - h_0)^2] + m_h \left( \frac{h - h_0}{2} \right)^2 \\
I_{z1} = \frac{1}{12} m_0 (a_0^2 + b_0^2) + \frac{1}{12} m_h (a^2 + b^2)
\]

(2)

\[
I_{x1} = \frac{1}{12} m_0 (a_0^2 + h_0^2) + m_0 \left( \frac{h_0}{2} + h_1 \right)^2 + \frac{1}{12} m_h [a^2 + (h - h_0)^2] + m_h \left( \frac{h - h_0}{2} \right)^2 \\
I_{y1} = \frac{1}{12} m_0 (b_0^2 + h_0^2) + m_0 \left( \frac{h_0}{2} + h_1 \right)^2 + \frac{1}{12} m_h [b^2 + (h - h_0)^2] + m_h \left( \frac{h - h_0}{2} \right)^2 \\
I_{z1} = \frac{1}{12} m_0 (a_0^2 + b_0^2)
\]

(3)

**Figure 1.** A simplified model diagram of the liquid tank

where \( m_0 = \rho a_0 b_0 \), \( m_h = \rho a_0 b (h - h_0) \), and \( \rho \) is the density of pesticide.

When \( h < h_0 \), the rotational inertia can be expressed as:

\[
I_{x1} = \frac{1}{12} m_0 (a_0^2 + h^2) + m_0 (h_0 + h_1 - \frac{h}{2})^2 \\
I_{y1} = \frac{1}{12} m_0 (b_0^2 + h^2) + m_0 (h_0 + h_1 - \frac{h}{2})^2 \\
I_{z1} = \frac{1}{12} m_0 (a_0^2 + b^2)
\]

(4)

3. **Attitude Controller Design**

With reference to the controller design procedure proposed in literature [14], an attitude angle controller is designed. First, the angular motion equations in Equation (1) are rewritten in the form of a state equation:

\[
\begin{align*}
    x_1 &= f_1 + g_1 u_\phi + \Delta_1 \\
    x_2 &= f_2 + g_2 u_\phi + \Delta_2 \\
    x_3 &= f_3 + g_3 u_\phi + \Delta_3
\end{align*}
\]

(5)

where \( \Delta_1 \), \( \Delta_2 \) and \( \Delta_3 \) are unknown disturbances, and other parameters are given by
\[
[x_1, x_2, x_3]^T = [\phi, \dot{\phi}, \psi]^T \quad [g_1, g_2, g_3]^T = \left[ \frac{I_y}{I_z}, \frac{I_z}{I_x}, \frac{I_x}{I_y} \right]^T
\]
\[
[f_1, f_2, f_3]^T = \left[ \frac{\partial \psi}{I_y} \frac{I_z - I_x}{I_x} + \frac{J_r}{I_y} \phi \Omega, \psi \phi \frac{I_z - I_x}{I_x} - \frac{J_r}{I_y} \phi \Omega, \phi \frac{I_z - I_x}{I_x} \right]^T
\]

(6)

The controller design process is mainly divided into two parts. Taking the roll channel as an example, in view of Equation (4) and the controller design flow, we define:

\[
g_1(t) = 1 \quad \theta_1(t) = \psi_1(x) = d_1(t) = \phi_1(x) = 0 \quad \xi_1 = \lambda_1 = 1 \quad \beta_1(x) = 2
\]

then \( \alpha_1 \) and \( \hat{k}_1 \) can be expressed as:

\[
\alpha_1 = 2N(k_1)f(1, z_1) \quad \hat{k}_1 = 2(\parallel z_1 \parallel - \lambda_1)^2 \gamma(1, z_1)
\]

(8)

where \( \alpha_1 \) is the first virtual controller. The first Lyapunov function is defined as:

\[
V_1 = \frac{1}{3}(\parallel z_1 \parallel - \lambda_1)^3 \gamma(\lambda_1, z_1)
\]

(9)

The second part, let:

\[
\xi_2 = \lambda_2 = 1 \quad \theta_2(t) = 0 \quad d_2(t) = f_1 \quad \phi_2(x) = 1
\]

\[
\beta_2(x, \bar{x}, y_d) = x^2 + 10 + 3\exp(k_2^2)k_2^2 \quad \hat{k}_2 = \beta_2(x, \bar{x}, y_d)(\parallel z_2 \parallel - 1)^2 \gamma(1, z_2)
\]

(10)

then \( u \) and \( \hat{k}_2 \) can be expressed as:

\[
u = N(k_2)\beta_2(x, \bar{x}, y_d)f(1, z_2) \quad \hat{k}_2 = \beta_2(x, \bar{x}, y_d)(\parallel z_2 \parallel - 1)^2 \gamma(1, z_2)
\]

(11)

The second Lyapunov function is defined as:

\[
V_2 = \frac{1}{3}(\parallel z_2 \parallel - \lambda_2)^3 \gamma(\lambda_2, z_2)
\]

(12)

The stability of the control strategy has been proved in literature [14], so this paper will not repeat.

4. Simulation and Testing

In this section, the simulation based on MATLAB-Simulink platform is given to validate the proposed controller. The parameters of UAV are shown in Table 1.

| Table 1. Model parameters |
|---------------------------|
| Parameters | value | Parameters | value |
| \( I_{x0} \) / (kg \cdot m²) | 0.033 | \( v / m \) | 0.005 |
| \( I_{y0} \) / (kg \cdot m²) | 0.033 | \( \rho / (kg \cdot m^{-3}) \) | 0.001 |
| \( I_{z0} \) / (kg \cdot m²) | 0.052 | \( a / m \) | 0.300 |
| \( I / m \) | 0.680 | \( b / m \) | 0.200 |
| \( J / (kg \cdot m²) \) | 1.120e-4 | \( h_0 / m \) | 0.200 |
| \( K_i \) | 0.012 |
The controller’s parameters need to be adjusted before used, and the parameters $\xi$ and $\lambda$ should be greater than 0 according to [14], so in this paper $\xi = 1$. But the value of $\lambda$ cannot be selected at random. When the value of $\lambda$ tends to 0, the function $f$ in Equation (10) will be equivalent to the symbolic function, which will make the value of $f$ switch between -1 and +1 when the independent variable changes near 0. In actual application, noise is inevitable, which will make this phenomenon more serious, and eventually causes the system output to fluctuate greatly.

In order to select a suitable value range, the step signals with step time of 2s and final values of 2, 4 and 8 were used as the system input to carry out simulation experiments. The simulation time was set to 20s, and the root mean square (RMS) error diagrams of system output were obtained as shown in Figure 2. According to the error curves, when the parameter $\lambda$ is less than 0.5, the system output fluctuation caused by function $f$ is obviously large, and the error is relatively low in the range of 0.5-7, but the error tends to increase with the increase of parameter value. Therefore, in actual application, the range of parameter value should be between 0.5-7, and fine-tuning should be carried out according to the actual error level. The tuned parameters of BTSMC and RBAC controllers are shown in Table 2.

For simplicity, $\lambda_i$ and $\xi_i$ ($i = 1, 2$) in this paper are chosen as $\lambda_i = \xi_i = 1$, and parameters of BTSMC are chosen the same as those in literature [12].

Table 2. Parameters of controllers

| Parameters | BTSMC value | RBAC value |
|------------|-------------|-------------|
| $c_i$      | 2           | 1           |
| $\beta$    | 15          | $\lambda_1$ | 1 |
| $\eta$     | 2           | $\lambda_2$ | 1 |
| $q$        | 7           | $\xi_1$     | 1 |
| $k_i$      | -2          | $\xi_2$     | 1 |

Figure 2. RMS error of different final value
4.1 Comparison of Control Effects in the Absence of Disturbance

Firstly, the control system was tested by simulating without disturbance. The initial condition of attitude angle was set as \((\phi, \theta, \psi) = (0,0,0)\) and the desired value was \((4,2,8)\). In this paper, the settling time is taken as an index to measure the dynamic performance of the system. The response curves of the roll channel are shown in Figure 3, 4 and 5, and the settling time of each channel is shown in Table 3. It can be seen that the control effect of RBAC is better than that of BTSMC, the attitude angle value converges to the desired value faster, the settling time of three attitude angle channels is shortened by 512.889ms, 489.099ms and 212.000ms respectively.

| Channel    | RBAC (ms) | BTSMC (ms) | Reduced settling time (ms) | Percent improvements (%) |
|------------|-----------|------------|----------------------------|--------------------------|
| Roll channel | 289.111   | 802.000    | 512.889                    | 63.95                    |
| Pitch channel | 700.901   | 1190.000   | 489.099                    | 41.10                    |
| Yaw channel  | 641.000   | 853.000    | 212.000                    | 24.85                    |

Figure 3. Response curve in the roll channel

Figure 4. Response curve in the pitch channel

Figure 5. Response curve in the yaw channel
4.2 Performance Tests on the Plugging Proppants

In order to further verify the effect of controller, in the roll channel, white noise whose power is 0.001w was added in the control process, with a sampling time of 0.01s. In the presence of disturbance, RBAC and BTSMC were compared, and results are shown in Figure 6.

![Figure 6. Response curve of the roll channel with disturbance](image)

From the simulation results, it can be seen that both methods are insensitive to external disturbances and have strong robustness. Selecting 16s-40s as the computational interval and taking a sample point every 0.1 second, the RMS errors of BTSMC and RBAC is 1.77° and 1.76° respectively. The disturbance rejection ability of the two control methods is similar to each other.

5. Conclusion

In this paper, a robust backstepping control strategy for attitude control of the multi-rotor plant protection UAV is studied. Based on the general dynamic model of the multi-rotor plant protection UAV, a robust backstepping controller is designed and its stability is analysed. The reasonable range of controller parameters is obtained by analysing the root mean square error of the system with different inputs. Finally, the simulation experiment of attitude tracking is carried out. The results show that compared with BTSMC, RBAC can effectively improve the dynamic performance of the system, and has the disturbance rejection ability which is similar to that of BTSMC.

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