Prescribed Performance Adaptive Fixed-Time Attitude Tracking Control of a 3-DOF Helicopter with Small Overshoot

Xidong Wang

Abstract—In this article, a novel prescribed performance adaptive fixed-time backstepping control strategy is investigated for the attitude tracking of a 3-DOF helicopter. First, a new unified barrier function (UBF) is designed to convert the prescribed performance constrained system into an unconstrained one. Then, a fixed-time (FxT) backstepping control framework is established to achieve the attitude tracking. By virtue of a newly proposed inequality, a non-singular virtual control law is constructed. In addition, a FxT differentiator with a compensation mechanism is employed to overcome the matter of “explosion of complexity”. Moreover, a modified adaptive law is developed to approximate the upper bound of the disturbances. To obtain a less conservative and more accurate approximation of the settling time, an improved FxT stability theorem is proposed. Based on this theorem, it is proved that all signals of the system are FxT bounded, and the tracking error converges to a preset domain with small overshoot in a user-defined time. Finally, the feasibility and effectiveness of the presented control strategy are confirmed by numerical simulations.

Index Terms—Unified barrier function (UBF), non-singular virtual control law, adaptive law, FxT stability theorem, 3-DOF helicopter.

I. INTRODUCTION

In recent decades, as one of the typical rotorcrafts, the helicopter has been paid substantial attention because of its widespread applications in various scenarios [1]. However, the high-performance tracking control design of the helicopter remains a challenging project due to the characteristics of the system [2].

Owing to the advantages of high tracking accuracy, fast response, and anti-interference capability, finite-time (FnT) control approaches have become a research hotspot [3]. Recently, a variety of FnT control schemes have been developed and applied to the 3-DOF helicopter platform (Fig. 1). In [4], a robust regulation controller for the laboratory helicopter was constructed based on the super-twisting sliding mode observer (STSMO), which was utilized to estimate the lumped disturbances and identify the state vector in finite time. To tackle the problem that the upper bound of disturbance is usually unknown in advance, the authors in [5] developed an adaptive-gain super-twisting algorithm for the tracking control of the helicopter platform. In [6], an adaptive FnT control law based on a continuous differentiator was presented for the lab helicopter system, which can effectively suppress chattering. An adaptive smooth FnT control protocol, integrated with a singularity-free integral sliding mode surface, was established to fulfill the helicopter attitude tracking in [7]. In [8], a novel control strategy, which embraced a modified FnT backstepping controller based on a newly designed disturbance observer, was presented for the tracking problem of the lab helicopter platform.

The drawback of the above strategies is that the settling time is related to the initial conditions, which is difficult to obtain accurately in many practical systems. Moreover, when the initial states are far from the equilibrium points, the settling time will become longer. To work out this problem, the FxT stability was first put forward in [9], where the settling time has no connection with the initial values. Thereafter, numerous FxT control approaches were developed to solve the control problems of different kinds of systems [10]–[13].

Although the above-mentioned control laws can fulfill the satisfactory steady-state performance, the tracking errors’ transient behavior is seldom taken into account. For the sake of addressing this problem, a prescribed performance control approach was first presented in [14], which introduced the concepts of error transformation and performance function (PF) to guarantee the behavior at both transient and steady
The definitions of variables and the values of parameters can be found in [7].

The control aim is to design a prescribed performance FxT control protocol such that the tracking errors can converge to a predetermined domain with small overshoot in a user-defined time, while all signals of the system are bounded within a fixed time.

**Assumption 1:** The desired tracking signals $x_{1d}(t), x_{3d}(t)$ and their derivatives are bounded, smooth and known.

**Assumption 2:** The disturbances are bounded as well as smooth.

**B. Improved FxT stability**

**Lemma 1:** Consider the following system

$$\dot{x}(t) = f(x(t)), x(0) = x_0$$

where $x \in \mathbb{R}^n$, $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ and $f(0) = 0$. If there exists a continuous Lyapunov function $V(x)$ satisfying:

$$\dot{V}(x(t)) \leq -\mu_1 V(x(t))^p - \mu_2 V(x(t))^q + \mu_3$$

where $\mu_1 > 0, \mu_2 > 0, 0 < \mu_3 < \infty, 0 < p < 1, q > 1$, then the origin of system (2) is practical FxT stable, and the residual set is bounded by:

$$F_x = \left\{ x : V(x) \leq \min \left\{ \left( \frac{\mu_3}{(1 - \tau) \mu_1} \right)^{\frac{1}{p}}, \left( \frac{\mu_3}{(1 - \tau) \mu_2} \right)^{\frac{1}{q}} \right\} \right\}$$

where $\tau \in (0, 1)$. Moreover, the settling time $T$ can be estimated by:

$$T \leq T_1 = \max \left\{ \frac{\Gamma \left( \frac{1-p}{q-p} \right) \Gamma \left( \frac{q-1}{q-p} \right) \left( \frac{\mu_1}{\mu_1(q-p)} \right)^{\frac{1-p}{q-p}}, \frac{\Gamma \left( \frac{1-p}{q-p} \right) \Gamma \left( \frac{q-1}{q-p} \right) \left( \frac{\tau_1}{\tau_1(q-p)} \right)^{\frac{1-p}{q-p}}} {\tau_1 \Gamma \left( \frac{q-1}{q-p} \right) \left( \frac{\mu_2}{\mu_2} \right)^{\frac{1-p}{q-p}}} \right\}$$

where $\Gamma(z) = \int_0^{+\infty} \exp(-\theta) \theta^{z-1} d\theta$ is the gamma function.

**Proof:** For a scalar $\tau \in (0, 1)$, (3) can be rewritten as

$$\dot{V}(x) \leq -\tau \mu_1 V(x)^p - (1 - \tau) \mu_1 V(x)^p - \mu_2 V(x)^q + \mu_3$$

or

$$\dot{V}(x) \leq -\mu_1 V(x)^p - \tau \mu_2 V(x)^q - (1 - \tau) \mu_2 V(x)^q + \mu_3$$

Then using Proposition 1 in [18], the approximation of the settling time (5) can be obtained.

**Remark 1:** The classical result for the approximation of the settling time is [19], [20]

$$T_2 = \frac{1}{\tau \mu_1 (1-p)} + \frac{1}{\tau \mu_2 (q-1)}$$

It can be proved that $T_1 < T_2$, which means that Lemma 1 provides a less conservative and more accurate approximation of the settling time than the classical result.
Remark 2: Denote \( l = \frac{1-p}{q-p} \). By means of \( \Gamma(l) \), \( (1-l) = \frac{\pi}{\sin(l\pi)} \), \( T_1 \) can be rewritten as
\[
T_1 = \max \left\{ \frac{\pi}{\mu_1 (q-p) \sin(l\pi)} \left( \frac{\mu_3}{\mu_2} \right)^{1/q} \right\}
\]
(9)

Lemma 3: If \( p+q = 2 \), the settling time \( T \) of Lemma 1 can be further estimated by:
\[
T \leq \tilde{T} \cdot \max \left\{ \frac{2}{1 - \arctan \left( \sqrt{\frac{\mu_3}{\mu_2}} \left( \frac{\mu_3}{(1-\tau)\mu_1} \right)^{1/q} \right)} \right\}
\]
where \( \tilde{T} = \frac{1}{(1-p/\sqrt{\mu_1 \mu_2})} \).

The result of Lemma 2 can be extended to the following more general forms:

Lemma 4: If \( (a-q)p+q = a \) with \( a \geq 2, a \in \mathbb{N}^+ \), the settling time \( T \) is approximated by \( T \leq \max \{ T_3, T_4 \} \), where
\[
T_3 = T_3 \left( \frac{\pi}{a \sin \left( \frac{\pi}{a} \right)} - I_a \left( \frac{\mu_3}{\mu_1} \right)^{1/q} \left( \frac{\mu_3}{(1-\tau)\mu_1} \right)^{1/q} \right)
\]
(11)
\[
T_4 = T_4 \left( \frac{\pi}{a \sin \left( \frac{\pi}{a} \right)} - I_a \left( \frac{\mu_3}{\mu_1} \right)^{1/q} \left( \frac{\mu_3}{(1-\tau)\mu_2} \right)^{1/q} \right)
\]
(12)
with \( T_3 = a (2k-1), T_4 = \frac{(1-p/\sqrt{\mu_1 \mu_2})^{1/q}}{a} \), \( \varphi_k = \frac{\tau_3}{\tau_2} \), \( \varphi_k = \frac{\tau_3}{\tau_2} \), \( \varphi_k = \frac{\tau_3}{\tau_2} \), \( \varphi_k = \frac{\tau_3}{\tau_2} \).

Lemma 5: For any variables \( \psi_1, \psi_2 \in \mathbb{R} \), and constants \( 0 < \gamma_1, \gamma_2 > 0 \), we have
\[
|\psi_1|^{\gamma_1} |\psi_2|^{\gamma_2} \leq \frac{\gamma_1}{\gamma_1 + \gamma_2} |\psi_1|^{1+\gamma_2} + \frac{\gamma_2}{\gamma_1 + \gamma_2} |\psi_2|^{1+\gamma_1}
\]
(16)

Lemma 6 ([24]): For \( \chi_k \in \mathbb{R}, k = 1, 2, \ldots, s, 0 < h \leq 1 \), one has
\[
\left( \sum_{k=1}^{s} |\chi_k|^h \right)^{1/h} \leq \left( \sum_{k=1}^{s} |\chi_k|^h \right)^{1/h}
\]
(17)

Lemma 7 ([8]): For any variable \( w \in \mathbb{R} \) and constants \( \delta > 0, \varepsilon > 0 \), it holds that
\[
0 \leq |w| - w^2 \sqrt{w^2 + \delta^2 + \varepsilon^2} < \frac{\varepsilon \delta}{\sqrt{\varepsilon^2 + \delta^2}}
\]
(18)

III. MAIN RESULTS

This section will provide the detailed design process of the elevation angle tracking control.

A. New UBF Design

The following PFs [25] are adopted as constraints on the tracking error \( e_1 = x_1 - x_{1d} \)
\[
K_1(t) = \left( e_1(0) - \Delta - e_\infty \right) \frac{1-e^{-\frac{t}{T_1}}} {1-e^{-\frac{t}{T_1}}} - e_\infty, t \in [0, T_s]
\]
(21)
\[
K_u(t) = \left( e_1(0) + \Delta - e_\infty \right) \frac{1-e^{-\frac{t}{T_1}}} {1-e^{-\frac{t}{T_1}}} + e_\infty, t \in [0, T_s]
\]
(22)
where \( T_s > 0, e_\infty > 0, \Delta > 0, e_\infty > 0, \Delta > 0 \) need to be designed.

Moreover, inspired by [25], we can also design the following novel PFs with the same properties as (21), (22): i)
\[
K_1(t) = \left( e_1(0) - \Delta + e_\infty \right) \frac{1-e^{-\frac{t}{T_1}}} {1-e^{-\frac{t}{T_1}}} + e_\infty, t \in [0, T_s]
\]
(23)
\[
K_1(t) = \left( e_1(0) + \Delta - e_\infty \right) \frac{1-e^{-\frac{t}{T_1}}} {1-e^{-\frac{t}{T_1}}} + e_\infty, t \in [0, T_s]
\]
(24)
ii)
\[
K_2(t) = \left( e_1(0) - \Delta + e_\infty \right) \frac{1-e^{-\frac{t}{T_1}}} {1-e^{-\frac{t}{T_1}}} + e_\infty, t \in [0, T_s]
\]
(25)
\[
K_2(t) = \left( e_1(0) + \Delta - e_\infty \right) \frac{1-e^{-\frac{t}{T_1}}} {1-e^{-\frac{t}{T_1}}} + e_\infty, t \in [0, T_s]
\]
(26)
iii) \[ K_{3u}(t) = \begin{cases} 
\frac{(e_{2i} t) - \Delta \epsilon_{\infty}}{\epsilon_{\infty}} & \text{if } 0 \leq t < T_s \\
-\epsilon_{\infty}, & \text{if } t \geq T_s 
\end{cases} \]

where \( e_{2i}, e_{3u}, \) and \( \epsilon_{\infty} \) are positive odd integers, and \( e_{2i} > 0, e_{3u} > 0, \epsilon_{\infty} > 0 \) are suitable designed parameters.

To achieve \( K_1(t) < e_1 < K u(t) \), a new UBF is developed as follows:

\[ z_1 = \frac{c_1}{(K_1(t) - e_1)^m} \left[ \frac{c_2}{(K_u(t) - e_1)^n} \right] \]

where \( m = m_2/m_1, n = n_2/n_1, m_2 > m_1 > 0, n_2 > n_1 > 0, \) and \( c_1, c_2 > 0 \) are suitable designed parameters.

It is easy to verify that when \( e_1 \to K_1(t) \), \( z_1 \to -\infty \) and \( e_1 \to K_u(t) \), \( z_1 \to +\infty \). Therefore, if \( z_1 \) is bounded, the tracking error can stay in the prescribed domain.

Furthermore, we construct the following new UBF, which can handle both restrained and unrestrained cases in a unified control structure:

\[ z_1 = \frac{(K_1(t) - e_1)^m e_1 + c_1}{2(K_1(t) - e_1)^m + (K_u(t) - e_1)^n e_1 + c_2} \]

**Remark 3:** By selecting appropriate designed parameters, the newly developed UBFs can effectively diminish the consumption of the control input energy caused by the introduction of constraints.

**B. Control Law Design**

Differentiating \( z_1 \) yields:

\[ \dot{z}_1 = \eta_1 \dot{e}_1 + \eta_2 \]

Then the tracking errors with compensation signals \( \xi_1, \xi_2 \) are developed as:

\[ w_1 = z_1 - \xi_1 \]
\[ w_2 = x_2 - x_1, f - \xi_2 \]

where \( x_1, f \) is acquired from the following FxT differentiator [26] with the non-singular virtual control law \( \alpha_1 \) as input.

\[ \dot{x}_{1,f} = -k_{1f} \phi_1(\sigma_f) + x_{2,f} \]
\[ \dot{x}_{2,f} = -k_{2f} \phi_2(\sigma_f) \]

where

\[ \phi_1(\sigma_f) = \sin(\sigma_f) \quad \phi_2(\sigma_f) = \frac{1}{2} \text{sign}(\sigma_f) + 2 \mu_f \sigma_f + \frac{3}{2} \mu_f^2 \text{sign}(\sigma_f)^2 \]

with \( \sigma_f = x_1, f - \alpha_1, \mu_f > 0 \).

The compensation variables \( \xi_1, \xi_2 \) are introduced as below [17]

\[ \xi_1 = -k_{11} \xi_1^p - k_{12} \xi_1^q + \eta_1 (x_1, f - \alpha_1) + \eta_1 \xi_2 \]
\[ \xi_2 = -k_{21} \xi_2^p - k_{22} \xi_2^q - \eta_1 \xi_1 \]

where \( 1/2 < p = p_2/p_1 < 1, q = q_2/q_1 > 1, p_1, p_2, q_1, q_2 \) are positive odd integers, and \( k_{11} > 0, k_{12} > 0, k_{21} > 0, k_{22} > 0 \) are suitable designed parameters.

Then the novel non-singular virtual control law \( \alpha_1 \) and FxT control signal \( \dot{u}_1 \) are constructed as follows:

\[ \alpha_1 = x_{1d} - \frac{1}{\eta_1} (y_2 + k_{12} w_1^q) \]
\[ + k_{11} w_1^{1+2p} \sqrt{\frac{w_1^{2+2p} + \delta_1^2 + \varepsilon_1^2}{(w_1^{2+2p} + \varepsilon_1^2) (w_1^{2+2p} + \delta_1^2)}} \]
\[ \dot{u}_1 = \frac{J_a}{L_a} \left( -k_{21} w_2 + k_{22} w_2^2 + \frac{g}{J_a} m_e \omega(x_1) \right) \]
\[ + \dot{x}_{1,f} - \eta_1 \dot{z}_1 - \hat{\xi}_1 w_2 \sqrt{\frac{w_2^2 + \delta_2^2 + \varepsilon_2^2}{(w_2^2 + \varepsilon_2^2) (w_2^2 + \delta_2^2)}} \]

where \( \hat{\xi}_1, \dot{\xi}_1 \) is the modified adaptive term to compensate the disturbance, which is developed as below

\[ \hat{\Omega} = \lambda_1 \left[ w_2^2 \sqrt{\frac{w_2^2 + \delta_2^2 + \varepsilon_2^2}{(w_2^2 + \varepsilon_2^2) (w_2^2 + \delta_2^2)}} - \lambda_2 \hat{\xi}_1 - \lambda_3 \hat{\xi}_1 \right] \]

where \( \lambda_1 > 0, \lambda_2 > 0, \lambda_3 > 0 \) need to be designed.

**C. Stability Analysis**

**Theorem 1:** Considering the elevation channel of (1) with Assumptions 1-2, the UBF (29) or (30), the FxT differentiator (33) with compensation mechanism (35), the adaptive compensation term (37), the virtual control law and controller (36), the attitude tracking error converges to a predefined region within a designer-defined time while the whole variables of the system are FxT bounded.

**Proof:** The Lyapunov function is constructed as below

\[ V = \frac{1}{2} \lambda_1^{-1} \left( \hat{\Omega}_d - \dot{d}_1 \right)^2 + \frac{1}{2} \sum_{i=1}^{2} \left( w_i^2 + \zeta_i^2 \right) \]

Then when \( t > t_1 \), the derivative of \( V \) with respect to time is calculated as

\[ \dot{V} \leq - \left[ \left( k_{11} \frac{1}{1+p} - \frac{1}{2} \right) \xi_1^{1+p} + k_{21} \frac{1}{1+p} \xi_1^{1+p} + \sum_{i=1}^{2} \frac{k_{1i} p \xi_1^{1+p}}{1+p} \right] \]
\[ - \left[ \left( k_{12} \frac{1}{1+q} - \frac{1}{2} \right) \xi_1^{1+q} + k_{22} \frac{1}{1+q} \xi_1^{1+q} + \sum_{i=1}^{2} \frac{k_{2i} q \xi_1^{1+q}}{1+q} \right] \]
\[ - \frac{\lambda_2}{2} \left( \hat{\Omega}_d - \dot{d}_1 \right)^{1+q} + \frac{q}{1+q} \left( \hat{\Omega}_d - \dot{d}_1 \right)^{1+q} + \mu_3 \]

With the aid of Lemma 6, it follows from (39) that

\[ \dot{V}(x) \leq -\mu_1 V(x)^{1+p} - \mu_2 V(x)^{1+q} + \mu_3 \]

where \( \mu_1 > 0, \mu_2 > 0, \mu_3 > 0 \).
In light of Lemma 1, the closed-loop system is practical FxT stable, and $w_i, \zeta_i$ converge to the following residual set within a fixed time:

$$|w_i| \leq \min \left\{ \sqrt{2 \left( \frac{\mu_3}{1 - \tau} \frac{2}{\mu_1} \right)} , \sqrt{2 \left( \frac{\mu_3}{1 - \tau} \frac{2}{\mu_2} \right)} \right\}$$

$$|\zeta_i| \leq \min \left\{ \sqrt{2 \left( \frac{\mu_3}{1 - \tau} \frac{2}{\mu_1} \right)} , \sqrt{2 \left( \frac{\mu_3}{1 - \tau} \frac{2}{\mu_2} \right)} \right\}$$

(41)

Then $|z_i| \leq |w_i| + |\zeta_i|$ is bounded. According to the property of UBF (29) and (30), it is concluded that the tracking error can converge to a predefined domain within a designed-defined time.

This completes the proof.

IV. SIMULATION RESULTS

To verify the feasibility and effectiveness of the developed control protocol, numerical simulations are performed on the elevation channel. The state is initialized at $x_1(0) = -\frac{\pi}{18} (rad)$ and the disturbance is $d_1 = 0.3 \sin(2t)(rad/s^2)$. The given command is set as:

$$x_{1d}(t) = \frac{\pi}{18} \sin(0.3 \pi t - \frac{\pi}{2})$$

(42)

A. The effectiveness verification of the designed UBF

In this simulation study, the PF parameters are designed as: $T_s = 1.2, \Delta = 0.05, e_\infty = 0.03$, and the parameters of the developed control protocol are presented as follows: $k_{1i} = 1, k_{12} = 1.5, k_{21} = 2, k_{22} = 6, c_1 = c_2 = 1, \delta_1 = 0.1, p = \frac{3}{5}, q = \frac{3}{5}$. while $m = n = 1, \frac{1}{3}, \frac{1}{7}, \frac{1}{7}$ respectively to show the performance of the designed UBF. The UBF in [27] is also utilized as the contrasting method, which is marked as classical-UBF.

The numerical simulation results are plotted in Fig. 2 (a)-(b). It is observed that by selecting appropriate designed parameters, the newly developed UBF can effectively diminish the consumption of the control input energy caused by the introduction of constraints.

B. The simulation of attitude tracking control

In this study, the PF parameters are designed as: $T_s = 1.2, \Delta = 0.05, e_\infty = 0.01$, and the parameters of the designed UBF are selected as: $c_1 = c_2 = 0.2, m = n = \frac{1}{3}$, while the other parameters are identical to those in simulation I. The developed control protocol without PF, and the CFB algorithm in [2] without RBFNN are adopted as the contrasting approaches.

The curves of the tracking error are displayed in Fig. 3, which demonstrates that the attitude tracking error can converge to a predefined region within a designer-defined time. Furthermore, the tracking error owns better transient behavior, especially small overshoot.

V. CONCLUSION

A novel prescribed performance adaptive fixed-time backstepping control protocol was proposed in this article to tackle the attitude tracking problem of a 3-DOF helicopter subject to disturbances. A newly designed UBF was adopted to transform the prescribed performance constrained system into an unconstrained one. By virtue of an improved FxT backstepping control algorithm, the attitude tracking was fulfilled. A modified FxT stability theorem was presented to provide
a less conservative and more accurate approximation of the settling time than the classical result. Theoretical analysis proves that all signals of the system are FxT bounded, while the tracking error converges to a predetermined domain with small overshoot in a user-defined time. Simulation results show the feasibility and effectiveness of the presented control strategy.

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