Quadrotor vertical taking off and landing control based on backstepping and non-singular terminal sliding mode

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***Abstract*—In this study, quadrotor vertical taking off and landing (VTOL) control problem of a quadrotor is investigated. A control strategy which has an inner-outer loop structure is proposed. A backstepping based controller is designed for the outer loop to fulfill position tracking aim. The inner loop is regarded as a nominal system with lumped disturbances which contains parameter perturbations, external disturbances and coupling effects. An improved non-singular terminal sliding mode controller is proposed for the nominal system and a disturbance upper bound estimator is designed to restrain the lumped disturbance. Robust stability and tracking performance are achieved simultaneously.**

***Keywords*—quadrotor; trajectory tracking; backstepping; non-singular terminal sliding mode**

I. Introduction

Quadrotor is a special kind of under-actuated Unmanned Aerial Vehicle (UAV). Compared with other conventional UAVs, the quadrotors have more compact construction, higher mobility and flexibility. These enable the quadrotor easy to realize hover, vertical take off and landing(VTOL) and autonomously fly in complex environments. Quadrotors are widely applied in military, farming and forestry, meteorology and rescue [1]. Recent years, the quadrotors have got increasingly attention.

The past few decades have witnessed plenty of research for the control of a quadrotor and various control methods such as backstepping and sliding mode have been proposed. Backstepping is an effective nonlinear control method for special nonlinear systems. Because of its recursive feature, it can reduce the complexity of the system and many prior researches have proven it's good performance in quadrotor trajectory tracking control [2, 3]. Sliding mode control (SMC) which widely used in quadrotor control [4, 5] is derived from variable structure systems. It is a robust methodology that appropriate for a certain class of nonlinear systems. When there are bounded parametric uncertainties or other types of bounded uncertainties in the system, SMC could deal with uncertainties by using larger control volume [6].

Owing to the characteristics, the use of combination of backstepping and SMC have achieved satisfying control result. [7] divided the quadrotor into attitude-altitude subsystem and position subsystem. For the first subsystem, a second order terminal sliding mode control theory combined with backstepping and adaptive control strategy is proposed to achieve free chattering, finite time convergence tracking aims. An Integral-SMC based position controller is designed for the second subsystem and adaption laws are designed to estimate the unknown bound of disturbances. [8] developed a regular SMC controller and backstepping based controller for inner loop and outer loop respectively. However, the traditional linear hyperplane sliding mode based methods cannot ensure finite time convergence. Terminal sliding mode (TSM) which has been used in the control of rigid manipulators, offers superior properties such as fast, finite time convergence and this controller is particularly useful for high precision control as it speeds up the rate of convergence near an equilibrium point. Therefore, the terminal sliding mode (TSM) is suitable for attitude control of a quadrotor [9–11]. Its important to note that, the terminal sliding mode (TSM) has a singularity problem inherently. In [12], Feng proposed a global non-singular terminal sliding mode (NTSM) controller to solve the singularity problem. In [13], a backstepping non-singular terminal sliding mode controller was designed. In this control scheme, instead of regular control input, the derivative of control input is achieved from a NTSM second layer sliding manifold. Adaptive tune method is utilized to deal with bounded disturbances. However, when handling the disturbances in inner loop, Modirrousta [13] design the attitude controller under the assumption that the derivative of disturbances are bounded. In addition, most of similar researches also assume that the disturbances are slow time-varying or the derivative of disturbances are bounded [14], or the upper bound of disturbances can be known explicitly [15]. In practice, these assumptions sometimes may be invalid.

The main contribution of this paper as follows: First, an improved nonsingular sliding mode controller which offers fast and finite time convergence is applied to the inner loop to fulfill quickly and precisely attitude tracking and backstepping controller is designed for the outer loop. Second, an adaptive disturbance upper bound estimator is designed to compensate for the time-varying disturbance in inner-loop.

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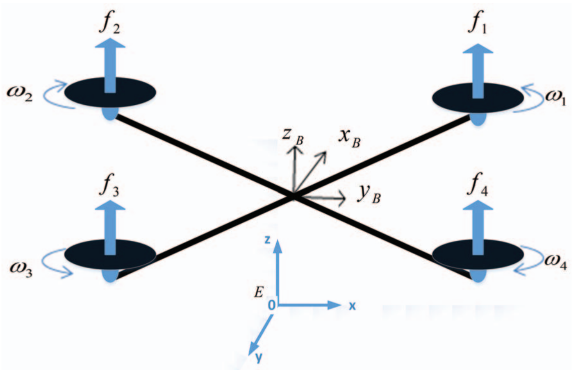


Fig. 1. Model of a quadrotor

The rest of this paper is organized as follows: the dynamic model of quadrotor is given in section 2. Section 3 presents the design procedure of the controller together with its stability analysis. Simulation results are presented in section 4. Conclusions are drawn in section 5.

II. Quadrotor Modeling

In this section, the dynamic model of quadrotor is described. As depicted in Fig.1, the dynamical model of the quadrotor is set up by the earth frame (donated by$\{E\}$) and body-fixed frame (donated by$\{B\}$). The kinematic equations [16–18] can be expressed by:

$$\begin{cases} \ddot{x} = -\frac{K_x}{m}\dot{x} + R_{1,3}u \\ \ddot{y} = -\frac{K_y}{m}\dot{y} + R_{2,3}u \\ \ddot{z} = -\frac{K_z}{m}\dot{z} + R_{3,3}u - g \end{cases} \tag{1}$$

$$\begin{cases} I_x\ddot{\phi} = -lK_\phi\dot{\phi} + \tau_1 + d_\phi \\ I_y\ddot{\theta} = -lK_\theta\dot{\theta} + \tau_2 + d_\theta \\ I_z\ddot{\psi} = -K_\psi\dot{\psi} + \tau_3 + d_\psi \end{cases} \tag{2}$$

where x , y and z are the position of quadrotor. m is total mass and R is rotation matrix (details see [19, 20]). K_x K_y K_z and K_ϕ K_θ K_ψ are air drag factor. I_x I_y and I_z denotes the inertia. u and τ are control inputs.

Depicted in Fig.1, the thrust f_i generated by rotor i is:

$$f_i = K_T\omega^2 \tag{3}$$

then the relationship between control inputs u , τ and thrust f_i are obtained:

$$\begin{array}{l} u = (f_1 + f_2 + f_3 + f_4)/m = T/m \\ \tau_1 = l(-f_1 - f_2 + f_3 + f_4) \\ \tau_2 = l(-f_1 + f_2 + f_3 - f_4) \\ \tau_3 = c(-f_1 + f_2 - f_3 + f_4) \end{array} \tag{4}$$

where l is the distance from the mass center to motors, K_T and c are constants known as thrust factor and force-to-moment scaling factor respectively.

Assumption 1. There is no prior knowledge about the lumped disturbances d_ϕ d_θ and d_ψ . The disturbances are bounded and upper bounds are defined as D_ϕ D_θ and D_ψ respectively.

III. Design of Control Strategy

In this section, the control design for quadrotor is presented. The control objective is to let the quadrotor track desired position X_d and desired yaw angle ψ_d under the control input u and τ.

A. Backstepping based controller design for altitude subsystem

The control objective of this section is to design input to ensure the tracking errors converge to zero asymptotically. Firstly, altitude controller is designed. From model equations (1), we obtain the altitude dynamic is:

$$\ddot{z} = -\frac{K_z}{m}\dot{z} + R_{3,3}u - g \tag{5}$$

let the error variables be defined as:

$$\xi_{z1} = z - z_d \tag{6}$$

$$\xi_{z2} = \dot{\xi}_{z1} + k_{z1}\xi_{z1} \tag{7}$$

where z_d is desired altitude, k_{z1} is a positive constant. The error variable dynamics can be obtained:

$$\dot{\xi}_{z1} = \xi_{z2} - k_{z1}\xi_{z1} = \dot{z} - \dot{z}_d \tag{8}$$

$$\begin{array}{r} \dot{\xi}_{z2} = \ddot{\xi}_{z1} + k_{z1}\dot{\xi}_{z1} \\ = -\frac{K_z}{m}\dot{z} + R_{3,3}u - g - \ddot{z}_d + k_{z1}(\xi_{z2} - k_{z1}\xi_{z1}) \end{array} \tag{9}$$

the altitude control input $R_{3,3}u$ is given by:

$$R_{3,3}u = \frac{K_z}{m}\dot{z} + g + \ddot{z}_d - (k_{z1} + k_{z2})\xi_{z2} + (k_{z1}^2 - 1)\xi_{z1} \tag{10}$$

Theorem 1. *The outer loop in (1) is stable under the control input (10), the position trajectory tracking error will converge to zero asymptotically.*

Proof. Without loss of generality, we chose the altitude subsystem to proof the theorem above.

Step 1

The Lyapunov candidate function chosen for this step is expressed as:

$$V_{z,1} = \frac{1}{2}\xi_{z1}^2 \tag{11}$$

then the derivative of $V_{z,1}$ with respect to time is given by:

$$\begin{array}{l} \dot{V}_{z,1} = \xi_{z1}\dot{\xi}_{z1} \\ = \xi_{z1}(\xi_{z2} - k_{z1}\xi_{z1}) \\ = -k_{z1}\xi_{z1}^2 + \xi_{z1}\xi_{z2} \end{array} \tag{12}$$

obviously, the sign of $\dot{V}_{z,1}$ is determined by $\xi_{z1}\xi_{z2}$.

Step 2

The Lyapunov candidate function for step 2 is defined as:

$$V_{z,2} = V_{z,1} + \frac{1}{2}\xi_{z2}^2 \tag{13}$$

we can get:

$$\begin{array}{l} \dot{V}_{z,2} = \dot{V}_{z,1} + \xi_{z2}\dot{\xi}_{z2} \\ = -k_{z1}\xi_{z1}^2 + \xi_{z1}\xi_{z2} + \xi_{z2}(-\frac{K_z}{m}\dot{z} \\ +R_{3,3}u - g - \ddot{z}_d + k_{z1}(\xi_{z2} - k_{z1}\xi_{z1})) \end{array} \tag{14}$$

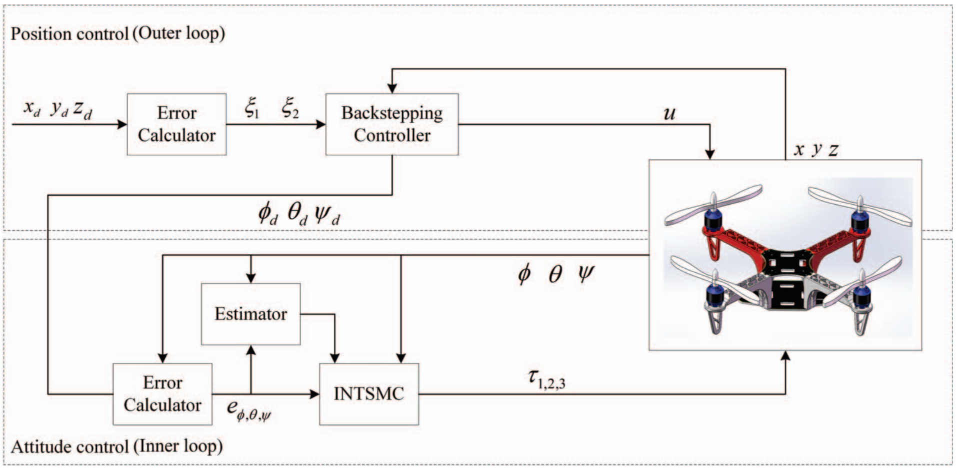


Fig. 2. Control structure

substituting (10) into (14), we obtained the following relationship:

$$\dot{V}_{z,2} = -k_{z1}\xi_{z1}^2 - k_{z2}\xi_{z2}^2 \tag{15}$$

obviously, $\dot{V}_{z,2} \leq 0$ It can be seen that under the control input (10), the stability of the altitude system can be guaranteed. Similarly, the stability of position subsystem $\{x\}$ and $\{y\}$ can also be guaranteed under the control input and adaption laws. □

From (1) and (4), we know that

$$\begin{bmatrix} R_{1,3}u \\ R_{2,3}u \\ R_{3,3}u \end{bmatrix} = \begin{bmatrix} c\phi s\theta c\psi + s\phi s\psi \\ c\phi s\theta s\psi - s\phi c\psi \\ c\phi c\theta \end{bmatrix} \frac{T}{m} \tag{16}$$

where s and c are short for trigonometric functions sin and cos. Note that in (16), there are three equations with four unknowns. Previous works[2, 8, 18, 21, 22] have done to solve the under-actuation. In this study, we let $\psi_d = 0$, then we can obtain

$$T = m\,\|U\| \qquad (U = \begin{bmatrix} R_{1,3}u & R_{2,3}u & R_{3,3}u \end{bmatrix}') \tag{17}$$

$$\phi_d = -\arcsin(\frac{R_{1,3}u}{\|U\|}) \tag{18}$$

$$\theta_d = \arctan(\frac{R_{1,3}u}{R_{3,3}u}) \tag{19}$$

B. Improved nonsingular terminal sliding mode based controller design for inner loop

The control objective in this section is to construct controller to ensure the roll angle ϕ and pitch angle θ tracking along the reference angle ϕ_d and θ_d robustly. This section propose a controller based on improved nonsingular terminal sliding mode [23]. To handle the bounded disturbance in the inner loop, we assume the upper bound of disturbance is D , and design adaption law is designed.

1) Improved nonlinear terminal sliding mode control design for nominal attitude system: In this subsection, an improved nonlinear terminal sliding mode attitude controller is designed for nominal attitude system. Given space limitations, we take the roll motion as an example to detail the controller designing process.

From (2), we know the roll motion nominal attitude dynamic is:

$$I_x\ddot{\phi} = -lK_\phi\dot{\phi} + \tau_1 \tag{20}$$

and the nominal INTSMC control input is chosen as:

$$\tau_1 = lK_\phi\dot{\phi} + \ddot{\phi}_d I_x - \Gamma_{\phi,1}\Gamma_{\phi,2}I_x - K_{s\phi}\mathrm{sgn}(s_\phi) \tag{21}$$

where $\Gamma_{\phi,i}(i = 1, 2, 3)$ are chosen as follows:

$$\begin{cases} \Gamma_{\phi,1} = 1 + \frac{r+1}{\alpha}\|e_{\phi,1}\|^r \\ \Gamma_{\phi,2} = \frac{\beta q}{p}e_{\phi,2}^{2-\frac{p}{q}} \\ \Gamma_{\phi,3} = \frac{p}{\beta q}e_{\phi,2}^{\frac{p}{q}-1} \end{cases}$$

Theorem 2. *Given the desired roll angle, the nominal roll motion closed-loop system is asymptotically stable under the control input τ_1 , and the system will reach the sliding surface in finite time.*

Proof. To prove the stability of nominal roll motion system , define the error variables as follows:

$$e_{\phi,1} = \phi - \phi_d \tag{22}$$

$$e_{\phi,2} = \dot{e}_{\phi,1} = \dot{\phi} - \dot{\phi}_d \tag{23}$$

then the sliding surface is chosen as [23]:

$$s_\phi = e_{\phi,1} + \frac{1}{\alpha}\|e_{\phi,1}\|^{r+1} + \frac{1}{\beta}e_{\phi,2}^{\frac{p}{q}} \tag{24}$$

where α , r and β are positive constants. p and q are positive odd numbers and satisfy the following constrain:

$$1 < \frac{p}{q} < 2 \tag{25}$$

A Lyapunov function $V_{\phi,1}$ is chosen as:

$$V_{\phi,1} = \frac{1}{2} I_x s_\phi^2 \tag{26}$$

The derivative of $V_{\phi,1}$ will be:

$$\begin{aligned}\dot{V}_{\phi,1} &= I_x s_\phi \dot{s}_\phi \\ &= s_\phi(\Gamma_{\phi,1} e_{\phi,2} I_x + \Gamma_{\phi,3}(-lK_\phi \dot{\phi} + \tau_1 - \ddot{\phi}_d I_x)\end{aligned} \tag{27}$$

Substituting the control input τ_1 into (27), we can obtain:

$$\begin{aligned}\dot{V}_{\phi,1} &= -K_{s\phi} s_\phi \Gamma_{\phi,3} \mathrm{sgn}(s_\phi) \\ &= -K_{s\phi} \Gamma_{\phi,3} |s_\phi|\end{aligned} \tag{28}$$

Note that $-K_{s\phi}\Gamma_{\phi,3}|s_\phi| \leq 0$ is beyond doubt. Based on the Lyapunov stability theorem, the nominal roll motion system is asymptotically stable. The system could reach the sliding surface in finite time , and following the proofs: From (24) we know that:

$$\begin{aligned}\dot{e}_{\phi,1} &= -\beta^{\frac{q}{p}} (e_{\phi,1} + \tfrac{1}{\alpha} \|e_{\phi,1}\|^{r+1})^{\frac{q}{p}} \\ &= -e_{\phi,1}^{\frac{q}{p}} (\beta(1 + \tfrac{1}{\alpha} e_{\phi,1}^r \mathrm{sgn}(e_{\phi,1})^{r+1}\end{aligned} \tag{29}$$

the integral of (29) is:

$$\begin{aligned}\int_{e_{\phi,1}(0)}^{e_{\phi,1}(t)} e_{\phi,1}^{-\frac{q}{p}} de_{\phi,1} &= -\int_0^t (\beta(1 + \tfrac{1}{\alpha} e_{\phi,1}^r \mathrm{sgn}(e_{\phi,1})^{r+1}))^{\frac{q}{p}} d\tau \\ &\leq -\int_0^t \beta^{\frac{q}{p}} d\tau\end{aligned} \tag{30}$$

and one can obtain:

$$t \leq \frac{p}{\beta^{\frac{q}{p}}(p-q)} e_{\phi,1}^{1-\frac{q}{p}}(0) \tag{31}$$

□

2) Disturbance upper bound estimator design: For a quadrotor, directly measure the disturbance is very difficult. This study proposed an alternative approach to cope with bounded disturbance. This section introduces an adaptive estimator to estimate the upper bound of the disturbance. For the roll motion, the estimator is:

$$\dot{\hat{D}}_\phi = s_\phi \Gamma_{\phi,3} \tag{32}$$

Theorem 3. *For the roll motion closed-loop system, under the Assumption, there exist efficient enough $K_{s\phi}$ that can guarantee the stability of the system with the nominal control input τ_1.*

Proof. An extended Lyapunov function $V_{\phi,2}$ is proposed as:

$$V_{\phi,2} = V_{\phi,1} + \frac{1}{2}(D_\phi - \hat{D}_\phi)^2 \tag{33}$$

combining Assumption1, we obtained the following relationship:

$$\dot{V}_{\phi,2} = s_\phi(\Gamma_{\phi,1} e_{\phi,2} I_x + \Gamma_{\phi,3}(-lK_\phi \dot{\phi} + \tau_1 + d_\phi - \ddot{\phi}_d I_x) - \dot{\hat{D}}_\phi (D_\phi - \hat{D}_\phi)) \tag{34}$$

Substituting (21),(32) into (34), then the above equation change into:

$$V_{\phi,2} = V_{\phi,1} + \frac{1}{2}(D_\phi - \hat{D}_\phi)^2 \tag{35}$$

Here we can see that, the stability of $V_{\phi,2}$ is determined by $(d_\phi - D_\phi)s_\phi - K_{s\phi}|s_\phi|$, since $\Gamma_3 \geq 0$ is beyond doubt. Note that $(d_\phi - D_\phi) \leq 0$, when $s_\phi \geq 0$, $\dot{V}_{\phi,2} \leq 0$ will be guaranteed. While, when $s_\phi < 0$, $\dot{V}_{\phi,2}$ can be rewritten as $\dot{V}_{\phi,2} = \Gamma_{\phi,3}|s_\phi|((D_\phi - d_\phi) - K_{s\phi})$. This indicate that $\dot{V}_{\phi,2} \leq 0$ when and only when $K_{s\phi} \geq (D_\phi - d_\phi)$. In conclusion, when the control coefficient $K_{s\phi}$ satisfy $K_{s\phi} \geq (D_\phi - d_\phi)$, $(d_\phi - D_\phi)s_\phi - K_{s\phi}|s_\phi| \leq 0$ holds. □

The pitch and yaw motion controller design are similar to the roll motion. And the control inputs and adaptive estimators are:

$$\begin{cases} \dot{\hat{D}}_\theta = s_\theta \Gamma_{\theta,3} \\ \tau_2 = lK_\theta \dot{\theta} - \hat{D}_\theta + \ddot{\theta}_d I_y - \Gamma_{\theta 1}\Gamma_{\theta 2} I_y - K_{s\theta}\mathrm{sgn}(s_\theta) \end{cases}$$

$$\begin{cases} \dot{\hat{D}}_\psi = s_\psi \Gamma_{\psi,3} \\ \tau_3 = K_\psi \dot{\psi} - \hat{D}_\psi + \ddot{\psi}_d I_z - \Gamma_{\psi,1}\Gamma_{\psi,2} I_z - K_{s\psi}\mathrm{sgn}(s_\psi) \end{cases}$$

IV. SIMULATION RESULTS

In this section, two cases of numerical simulations are conducted to verify the proposed control strategy. The simulations are conducted on Matlab/Simulink8.3.0.532 (R2014a), and equipped on a computer consisting of a Intel(R) Core I7-4790 @ 3.6GHz CPU with 8GB RAM and 1000GB solid state disk drive.

TABLE I
QUADROTOR MODEL PARAMETERS

Parameters	Values	Units
m	1.5	Kg
l	0.33	m
g	9.81	m/s^2
I_x, I_y	0.075	Ns^2/rad
I_z	0.13	Ns^2/rad
K_x, K_y, K_z	0.01	Ns/m
K_ϕ, K_θ, K_ψ	0.012	Ns/m
d_ϕ, d_θ, d_ψ	$0.05\sin(20t) + 0.05cos(10t) + 0.02$	$N \cdot m$

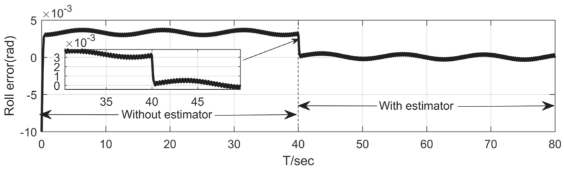
TABLE II
CONTROLLER PARAMETERS

Parameters	Values	Parameters	Values
K_{x1}, K_{y1}, K_{z1}	5	$K_{s\phi}$	3
K_{x2}, K_{y2}, K_{z2}	3	$K_{s\theta}$	3
α	2	$K_{s\psi}$	3
r	4	p	5
β	1	q	3

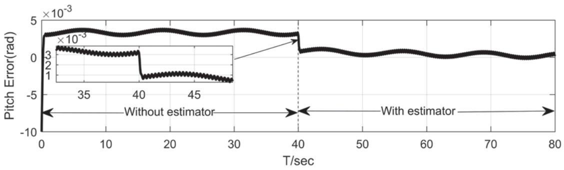
- Case 1
  This case demonstrate the effectiveness of the estimator in reducing the error of attitude tracking. The inertial attitude of the quadrotor is $\left[\begin{array}{ccc} 0.01 & 0.01 & 0.01 \end{array}\right]'(rad)$. The model parameters of quadrotor are shown in Table1 and controller parameters are listed in Table2. The desired attitude used in this case is $\left[\begin{array}{ccc} 0 & 0 & 0 \end{array}\right]'(rad)$. Figure3 shows the attitude control performances with and without the disturbance estimator. From Figure 3 we can see that under the control of nominal input, the attitude control

TABLE III
REFERENCE POSITION AND YAW ANGLE

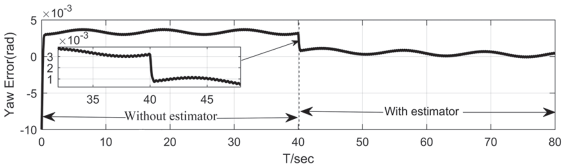
Parameters	Values		Units
$\begin{pmatrix} x_d & y_d & z_d \end{pmatrix}$	$\begin{pmatrix} 0 & 0 & 0 \end{pmatrix}$	$(t=0)$	m
	$\begin{pmatrix} 0 & 0 & 0.1t \end{pmatrix}$	$(0<t\leq 10)$	
	$\begin{pmatrix} 0 & 0 & 1 \end{pmatrix}$	$(10<t\leq 20)$	
	$\begin{pmatrix} 0 & 0 & 3-0.1t \end{pmatrix}$	$(20<t\leq 30)$	
ψ_d	0	$(0\leq t\leq 60)$	rad



(a) Roll motion error



(b) Pitch motion error

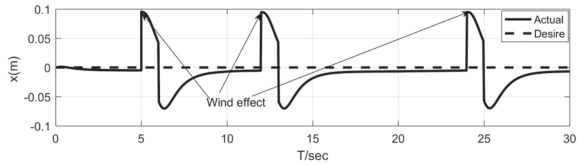


(c) Yaw motion error

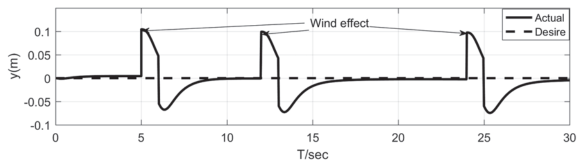
Fig. 3. Attitude tracking error

errors are about 0.4% , and at $t = 40s$, the estimators are induced and the errors decrease obviously. This results demonstrate the effectiveness of disturbance estimator in reducing effect of disturbance.

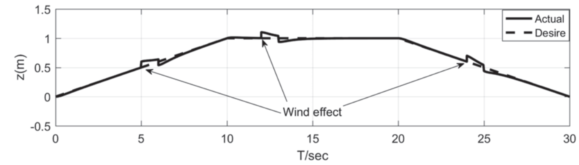
- Case 2
  In this case, the vertical take off and landing (VTOL) is conducted. The simulation consists of three parts: take off, hover and landing. In order to certificate the robust to external disturbance, we take wind effect (square signal) into consideration. Tab.3 shows the reference position and yaw angle. The inertial attitude of the quadrotor is $\begin{bmatrix} 0.01 & 0.01 & 0.01 \end{bmatrix}'(rad)$. Figure 4 shows the position control, and the tracking errors are shown in Figure 7.
  From Figure 4-5 we can see that the proposed control strategy hanve good control performance in VTOL and hovering and Figure7 indicate that the static errors are far less than 5%. At $t = 5, 12, 24s$, square signals are added into the system to verify the robust of the controller. Simulation results shows that the controller has strong robustness to the abrupt amplitude disturbance.



(a) X tracking error



(b) Y tracking error



(c) Z tracking error

Fig. 4. Position tracking response

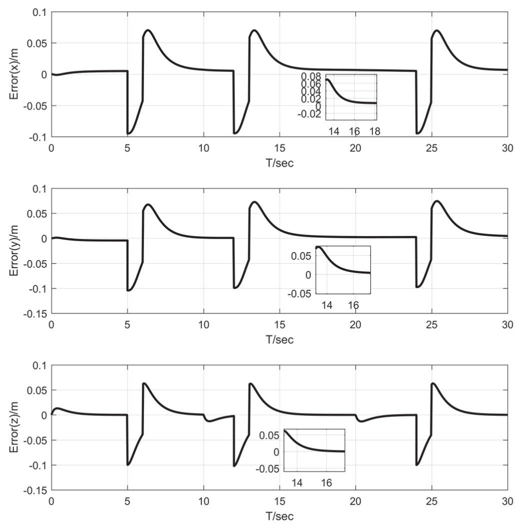


Fig. 5. Model of a quadrotor

V. CONCLUSION

In this paper, the trajectory tracking control for quadrotor in the presence of disturbance has been investigated. No prior knowledge of disturbance is required. During the controller design process, adaptive control theory is applied to estimate the the upper bound of disturbance. In addition, an improve nonsingular sliding mode based attitude controller and back-stepping position controller are proposed for inner loop and outer loop respectively. Numerical simulation results confirm the controller's good performance.

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