ROBUST DYNAMIC SLIDING MODE CONTROL BASED DISTURBANCE OBSERVER FOR QUADCOPTER UNMANNED AERIAL VEHICLE

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Abstract - This paper presents a robust dynamic sliding mode control method using a nonlinear disturbance observer for an unmanned aerial vehicle. The introduced algorithm is used to provide a fast adaptation and strictly robust for the attitude control of the vehicle. First, a nonlinear disturbance observer (NDO) is applied to estimate the external disturbance. Second, a robust dynamic sliding mode controller (SMC) combined with the estimated values of perturbationto compensate for the effect of these perturbations on the system. The stability of a control system is proven by Lyapunov theory. A numerical simulation was performed and compared to recently methods demonstrating the robustness and effectiveness of the proposed method.

Keywords - UAVs, Disturbance Observer, SMC, Quadcopter, Disturbance Elimination.

I. INTRODUCTION

Many studies have been introduced to attenuate the undesirable effects of perturbation on the engineering systems. SMC technique is well known for the robustness and efficiency of its control algorithm in a lot of complicated environments and system dynamics, because of its inherent abilityto eliminate external perturbations. [1-5] introduced a second order SMC to improve the tracking performance of the attitude control for quadcopter UAVs. Other approaches have been proposed in [6,7], an adaptive fuzzyPID based nonsingular fast terminal SMC is introduced to improve the robustness for stabilized control of a spacecraft. Although the combination of fuzzy technique and SMC algorithm can be used to enhance the control performance of a system, the quality of fuzzy controller almostdepends on an experience and knowledge of a controller designer about the engineering system and operational environment. Therefore, this method may not suitable for many systems. In [8], a robust nonlinear controller is proposed by an integration of backstepping technique and SMC methods to improve the tracking performance of the attitude and position of a UAV under bounded uncertainties and time-varying perturbations.

Other studies to attenuate the effects of uncertainties are proposed by using disturbance observer techniques to estimate the external perturbation from the measurable states, and then, many kind of controller are also designed to compensate for the effect of these uncertainties [9-12]. Although the control performance is enhanced, the chattering effect is still existent due to a discontinuous term of the switching control law. The motivation of this study is to design a superior controller with high quality robustness, fast adaptation without chattering effect on an engineering system.

II. QUADCOPTERS MODELING

The quadcopter model is presented in many existent approaches [13-16]. The basic frames consist of an Earth frame, {E}, and body frame, {B}, as shown in Figure 1.

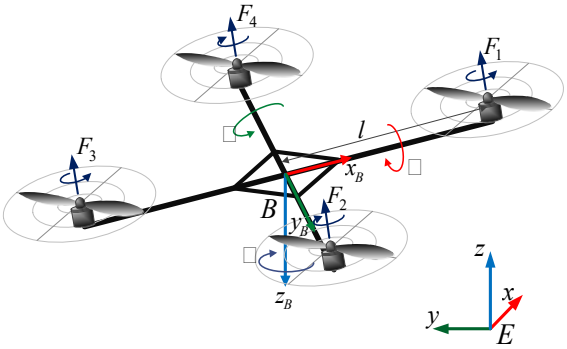


Figure 1: Quadcopter's model

Let $f, q, y \in \square$, $(-p/2 \le f \le p/2$, $-p/2 \le q \le p/2$, $-p \le y \le p)$, represent the Euler angle (roll, pitch and yaw), respectively; $x, y, z \in \square$ are the position in the {E}. F_i *(i=1,2,3,4)*denotes the thrust generated by motors *i*;Ω_I is the speed of the rotor *i*; x_f, x_q, x_y are external disturbances impacting on roll, pitch, yaw dynamics of the vehicle, respectively. In this study, the external disturbance is considered as a harmonic disturbance with unknown amplitude but known frequency described. The dynamics model of the vehicle including harmonic external disturbance (x_f, x_q, x_y) can be described as follows equations [13].

$$\begin{bmatrix} \ddot{f} \\ \ddot{q} \\ \ddot{y} \\ \ddot{z} \\ \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} \frac{I_{yy}-I_{zz}}{I_{xx}}\dot{q}\dot{y} + \dot{q}\frac{J_r}{I_{xx}}\Omega_r + \frac{l}{I_{xx}}U_2 \\ \frac{I_{zz}-I_{xx}}{I_{yy}}\dot{f}\dot{y} - \dot{f}\frac{J_r}{I_{yy}}\Omega_r + \frac{l}{I_{yy}}U_3 \\ \frac{I_{xx}-I_{yy}}{I_{zz}}\dot{q}\dot{f} + \frac{1}{I_{zz}}U_4 \\ g - \frac{(\cos f \cos q)U_1}{m} \\ \frac{U_1}{m}(\cos f \sin q \cos y + \sin f \sin y) \\ \frac{U_1}{m}(\cos f \sin q \sin y - \sin f \cos y) \end{bmatrix} + \begin{bmatrix} x_f(t) \\ x_q(t) \\ x_y(t) \\ x_h(t) \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

where $U_i \in \square$, $i = 1,2,3,4$ denote the control inputs of a quadrotor [13]:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \\ \Omega_r \end{bmatrix} = \begin{bmatrix} b\left(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2\right) \\ b\left(-\Omega_2^2 + \Omega_4^2\right) \\ b\left(\Omega_1^2 - \Omega_3^2\right) \\ d\left(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2\right) \\ -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4 \end{bmatrix} \quad (2)$$

Ω_r is the total residual angular speed of motors and g = 9.81m/s^2 denotes the gravitational acceleration. The remaining parameters from Eqs.(1) and (2) are shown in Table 1.

Parameters	Descriptions
I_{xx} , I_{yy} , I_{zz} (kgm^2)	Moments of inertia along three axes x,y and z in the Earth frame
m (kg)	Total mass of a quadcopter
l (m)	Arm length of the quadcopter frame
b (Ns^2)	Thrust coefficient
d (Nms^2)	Drag coefficient
J_r(kgm^2)	Moment of inertial of a rotor

Table1

Let X denotes a state vector defined by:

$$X = \left[x_1, x_2, ..., x_{12}\right]^T = \left[f, \dot{f}, q, \dot{q}, y, \dot{y}, z, \dot{z}, x, \dot{x}, y, \dot{y}\right]^T$$
$$\dot{X} = \left[\dot{x}_1, \dot{x}_2, ..., \dot{x}_{12}\right]^T = \left[\dot{f}, \ddot{f}, \dot{q}, \ddot{q}, \dot{y}, \ddot{y}, \dot{z}, \ddot{z}, \dot{x}, \ddot{x}, \dot{y}, \ddot{y}\right]^T$$

where $x_1 = f$, $x_2 = \dot{x}_1 = \dot{f}$, $x_3 = q$, $x_4 = \dot{x}_3 = \dot{q}$, $x_5 = y$, $x_6 = \dot{x}_5 = \dot{y}$, $x_7 = z$, $x_8 = \dot{x}_7 = \dot{z}$, $x_9 = x$, $x_{10} = \dot{x}_9 = \dot{x}$, $x_{11} = y$, $x_{12} = \dot{x}_{11} = \dot{y}$.

Eq.(1) can be re-written in state space by: $\dot{X} = f\left(X, U_i\right) + x_i$ where,

$$f\left(X, U_i\right) = \begin{bmatrix} x_2 \\ x_4 x_6 a_1 + x_4 a_2 \Omega_r + b_1 U_2 \\ x_4 \\ x_2 x_6 a_3 + x_2 a_4 \Omega_r + b_2 U_3 \\ x_6 \\ x_2 x_4 a_5 + b_3 U_4 \\ x_8 \\ g - (\cos x_1 \cos x_3) U_1 / m \\ x_{10} \\ (\cos x_1 \sin x_3 \cos x_5 + \sin x_1 \sin x_5) U_1 / m \\ x_{12} \\ (\cos x_1 \sin x_3 \sin x_5 - \sin x_1 \cos x_5) U_1 / m \end{bmatrix},$$

$$x_i(t) = \begin{bmatrix} 0 \\ x_f(t) \\ 0 \\ x_q(t) \\ 0 \\ x_y(t) \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \text{ and } \begin{cases} a_1 = \left(I_{yy} - I_{zz}\right)/I_{xx} \\ a_2 = J_r / I_{xx} \\ a_3 = \left(I_{zz} - I_{xx}\right)/I_{yy} \\ a_4 = \left(-J_r\right)/I_{yy} \\ a_5 = \left(I_{xx} - I_{yy}\right)/I_{zz} \\ b_1 = l/I_{xx} \\ b_2 = l/I_{yy} \\ b_3 = 1/I_{zz} \end{cases} \quad (3)$$

III. CONTROLLER DESIGN

A second order nonlinear system is considered by:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= f(x) + g(x)u + x(t) \\ y &= x_1 \end{aligned} \quad (4)$$

where $\boldsymbol{x} = \left[x_1, x_2\right]^T$, x_1 and x_2 are states of the system, y is output, $u \in R$ is the controller input, $f(x)$ and $g(x)$ are the smooth functions in term of $\boldsymbol{x}$, and $x(t) \in R$ is an external disturbance.

Eq.(1) can be re-written by:

$$\begin{cases} \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} x_2 \\ f(x) \end{bmatrix}}_{F(x)} + \underbrace{\begin{bmatrix} 0 \\ g(x) \end{bmatrix}}_{G_1(x)} u + \underbrace{\begin{bmatrix} 0 \\ 1 \end{bmatrix}}_{G_2(x)} x(t) \\ y = x_1 \end{cases} \quad (5)$$

3.1 Nonlinear Disturbance Observer (NDO)

Let us assume that the external disturbance is considered as a harmonic disturbance generated by:

$$\begin{cases} \dot{\Upsilon} = W\Upsilon \\ x = E\Upsilon \end{cases} \quad (6)$$

where $\Upsilon \in R^m$, W is an $m \times m$ matrix, and E is a row matrix $1 \times m$. Let $\hat{\Upsilon} \in R^m$ and $\hat{x} \in R$ are the estimates of Υ, x . $e = \left[e_1, ..., e_m\right]^T$, $e_1, ..., e_m \in R^+$ are constants to be given; L_F is a Lie derivative of function $F(x)$, and r is a relative degree from the disturbance to the output. Now, let us refers to the Chen's work [17], a nonlinear disturbance observer for a system as Eq.(5) is obtained as follows:

$$\begin{cases} \dot{z} = \left[W - l(x)G_2(x)E\right]z + Wp(x) \\ \qquad\quad - l(x)\left[G_2(x)Ep(x) + F(x) + G_1(x)u\right] \\ \hat{\Upsilon} = z + p(x) \\ \hat{x} = E\hat{\Upsilon} \end{cases} \quad (7)$$

Where

$$p(x) = eL_F H(x) = e\frac{\partial\left(H(x)\right)}{\partial x}F(x) = \begin{bmatrix} e_1 x_2 \\ e_2 x_2 \end{bmatrix}$$
$$l(x) = l(x) = \frac{\partial p(x)}{\partial x} = e\frac{\partial L_F^{r-1}H(x)}{\partial x} = \begin{bmatrix} 0 & e_1 \\ 0 & e_2 \end{bmatrix} \quad (8)$$

The NDO is shown in Figure 1.

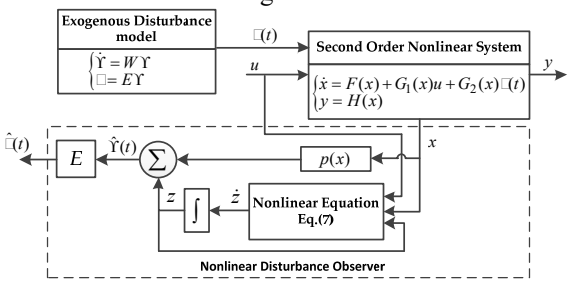


Figure 2. General structure of NDO for disturbances.

3.2 Robust Dynamic Sliding Mode Controller (RDSMC)

A robust dynamics sliding mode control method is introduced in this section. Let y_d is a desired state of the system in Eq.(4). The tracking error and its first derivative $e = y_d - y$, $\dot{e} = \dot{y}_d - \dot{x}_1$. The second derivative, $\ddot{e}$, can be computed by Eq.(1) as follows:

$$\ddot{e} = \ddot{y}_d - f(x) - g(x)u - x(t) \quad (9)$$

Choose a PID sliding surface

$$s(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \quad (10)$$

where $k_p, k_i, k_d \in \mathbb{R}^+$ are constants. We can see that

$$\dot{s}(t) = k_p \dot{e}(t) + k_i e(t) + k_d \ddot{e}(t) \quad (11)$$

From Eqs.(10) and (11), it can be seen that, if $s(t) = \dot{s}(t) = 0$, it implies that $e(t) \to 0$ when the k_p, k_i and k_d are appropriately chosen. Therefore, the characteristic polynomial in the right side of Eq.(11) $\left(k_p \dot{e}(t) + k_i e(t) + k_d \ddot{e}(t) = 0\right)$ is strictly Hurwitz. It means that the close loop control system is globally asymptotically stable.

Let $s(t)$ be a dynamic sliding surface given by:

$$s(t) = \dot{s}(t) + l\, s(t) \quad (12)$$

where $l > 0$, obviously, if value of $s = 0$, then the system: $\dot{s} + l\, s = 0$ is an asymptotically stable. From Eqs.(9),(11) and (12), $s(t)$ is computed by:

$$s(t) = k_p \dot{e}(t) + k_i e(t) + k_d \left(\ddot{y}_d - f(x) - g(x)u - x(t)\right) + l\, s(t) \quad (13)$$

and $\dot{s}(t)$, can be obtained by:

$$\dot{s} = k_d\left(\dddot{y}_d - \ddot{f}(x) - \ddot{g}(x)u - \dot{x}\right) - k_d g(x)\dot{u} + \left(k_p + k_d l\right)\left(\ddot{y}_d - f(x) - g(x)u - x\right) + \left(k_i + l\, k_p\right)\dot{e} + l\, k_i e \quad (14)$$

The proposed controller is designed as theorem 1.

Theorem 1: *Let us assume that* $\exists J, n, k_s \in R^+$ *are constant values and always satisfy bellow conditions:*

$$\begin{cases} \left|\tilde{x}(t)\right| \le n, \left|\dot{\tilde{x}}(t)\right| \le J \\ k_d J + \left(k_p + k_d l\right) n \le k_s \end{cases} \quad (15)$$

The sliding surface, $s(t)$ *, asymptotically converges to zero if a controller,* $\dot{u}$ *, is given as follows Eq.(16).*

$$\dot{u} = \frac{1}{k_d g(x)}\begin{pmatrix} k_d\left(\dddot{y}_d - \ddot{f}(x) - \ddot{g}(x)u - \ddot{\hat{x}}\right) \\ + \left(k_p + k_d l\right)\left(\ddot{y}_d - f(x) - g(x)u - \dot{\hat{x}}\right) \\ + \left(k_i + l\, k_p\right)\dot{e}(t) + l\, k_i e(t) + bs + k_s \operatorname{sgn}(s) \end{pmatrix} \quad (16)$$

Proof:

Substituting Eqs.(16) to Eq.(14):

$$\dot{s} = -k_d \ddot{\tilde{x}} - \left(k_p + k_d l\right)\dot{\tilde{x}} - bs - k_s \operatorname{sgn}(s) \quad (17)$$

Choose a Lyapunov function:

$$V_1 = \frac{1}{2}s^2 \quad (18)$$

The derivative of V_1 is obtanied from Eqs.(17) and (18) as follows:

$$\begin{aligned} \dot{V}_1 &= -bs^2 + s\left(-k_d \ddot{\tilde{x}} - \left(k_p + k_d l\right)\dot{\tilde{x}}\right) - k_s |s| \\ &\le -bs^2 + |s|\left(k_d J + \left(k_p + k_d l\right)n - k_s\right) \\ &\le -bs^2 < 0 \end{aligned} \quad (19)$$

$s(t)$, asymptotically converges to zero as the Lyapunov theory.

3.2 NDO-RDSMC for quadcopter UAVs

The roll dynamic described in Eq.(3) can be shown as follows equations:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = x_4 x_6 a_1 + x_4 a_2 \Omega_r + b_1 U_2 + x_f \end{cases} \quad (20)$$

Let defines $f_f(x) = x_4 x_6 a_1 + x_4 a_2 \Omega_r$, $g_f(x) = b_1$, and $F_f(x) = \left[x_2, f_f(x)\right]^T$, $G_1^f(x) = \left[0, g_f(x)\right]^T$, $G_2^f(x) = [0, 1]^T$, and $H_f(x) = x_1$. A NDO to estimate the external disturbance in roll dynamic is computed by Eq.(7), as follows:

$$\begin{cases} \dot{z}_f = \left[W_f - l_f(x)G_2^f(x)E_f\right]z_f + W_f p_f(x) \\ \quad - l_f(x)\left[G_2^f(x)E_f p_f(x) + F_f(x) + G_1^f(x)U_2\right] \\ \hat{\Upsilon}_f = z_f + p_f(x) \\ \hat{x}_f = E_f \hat{\Upsilon}_f \end{cases} \quad (21)$$

where

$$p_f(x) = \begin{bmatrix} e_1^f x_2 \\ e_2^f x_2 \end{bmatrix},\ l_f(x) = \begin{bmatrix} 0 & e_1^f \\ 0 & e_2^f \end{bmatrix},\ e_1^f, e_2^f > 0 \quad (22)$$

and U_2 is RDSMC controller. Let f_d be a desired state of roll control. The tracking error of roll angle and its first derivative are given by: $e_f = f_d - x_1$, $\dot{e}_f = \dot{f}_d - \dot{x}_1$, and $\ddot{e}_f(t) = \ddot{f}_d - f_f(x) - g_f(x)U_2 - x_f$. A sliding surface of roll control, s_f , and its derivative, $\dot{s}_f$, are chosen from as follows:

$$
\begin{aligned}
s_f(t) &= k_p^f e_f(t) + k_i^f \int_0^t e_f(t)dt + k_d^f \dot{e}_f(t) \\
\dot{s}_f(t) &= k_p^f \dot{e}_f(t) + k_i^f e_f(t) \\
&\quad + k_d^f \left(\ddot{f}_d - f_f(x) - g_f(x)U_2 - x_f \right)
\end{aligned} \tag{23}
$$

And controller U_2 is obtained from theorem 1.

$$
\dot{U}_2 = \frac{1}{k_d^f g_f(x)} \begin{pmatrix} k_d^f \left(\dddot{f}_d - \dot{f}_f(x) - \dot{g}_f(x)U_2 - \dot{\hat{x}}_f \right) \\ + \left(k_p^f + k_d^f l_f \right) \left(\ddot{f}_d - f_f(x) - g_f(x)U_2 - \hat{x}_f \right) \\ + \left(k_i^f + l_f k_p^f \right) \dot{e}_f \\ + l_f k_i^f e_f + b_f s_f + k_s^f \operatorname{sgn}(s_f) \end{pmatrix} \tag{24}
$$

The controller for Pitch and Yaw subsystem is entirely similar designed as the roll controller.

IV. SIMULATION RESULTS

The numerical simulation is performed in the attitude control of UAVs to demonstrate the strict robustness and efficiency of the proposed algorithm, presented in this section. The advantage of proposed controllers is discussed and compared to the recent studies such as NTSMC, STSMC , and M-STSMC. The numerical simulation is carried out through several assumptions: (i) The parameters of a quadcopter UAV, are given in Table 2 and Table 3; (ii) the dynamics of attitude (i.e. roll, pitch, and yaw) is simultaneously affected by the different external disturbances as:

$$
t \in [5,10]\sec : \begin{cases} x_f(t) = x_q(t) = (3t+5)\sin(2t+10) \\ x_y(t) = (2t)\sin(t+5) \\ x_h(t) = (3t+5)\sin(t+10) \end{cases}
$$

$$
t \in (0,5) \cup (10,+\infty)\sec : x_f(t) = x_q(t) = x_y(t) = x_h(t) = 0
$$

Parameters	Value and Unit
I_{xx} , I_{yy} , I_{zz} (kgm^2)	(0.0119, 0.0119, 0.0223) kg.m^2
m (kg)	1.12 kg
l (m)	0.23 m
b (Ns^2)	7.73213 (10^{-6})Ns^2
d (Nms^2)	1.27513 (10^{-7})Nms^2
J_r(kgm^2)	8.5(10^{-4}) kgm^2

Table 2

The performance of nonlinear disturbance observer of roll, pitch, yaw are shown in Figures3-5. It is easy to see that, the disturbance estimation values, $\hat{\xi}_\phi, \hat{\xi}_\theta, \hat{\xi}_\psi$, and asymptotically tracks the external disturbances.

The proposed NDO-RDSMC controller exhibits excellent tracking performance with a strict robustness with respect to other methods (i.e. M-STSMC, NTSMC, and STSMC): small oscillation and rapid convergence to a steady state, while other existent methods generated larger oscillation amplitude and result in an unstable performance of the system as shown in Figures 6-8.

Symbol	Roll (ϕ)	Pitch (θ)	Yaw (ψ)	Altitude (h)
k_p	0.5	0.5	0.5	1.0
k_i	0.001	0.001	0.001	0.001
k_d	0.008	0.008	0.008	0.1
λ	3.3	3.3	3.0	1.8
β	60	60	30	4.5
k_s	0.5	0.5	0.1	1.0
k_1	30	30	20	15
k_2	0.1	0.1	0.1	1.0
ε_1	10	10	10	10
ε_2	12	12	30	30

Table 3

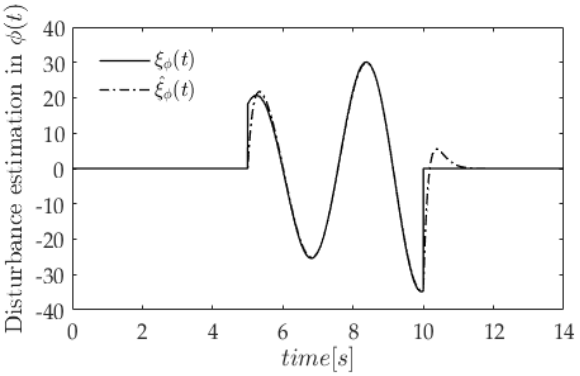


Figure 3. Disturbance estimation of in roll subsystem.

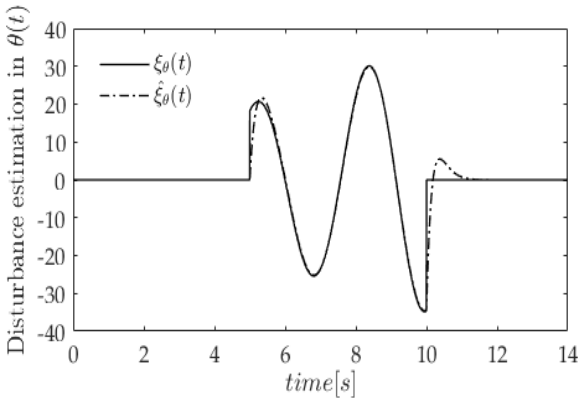


Figure 4. Disturbance estimation of in pitch subsystem.

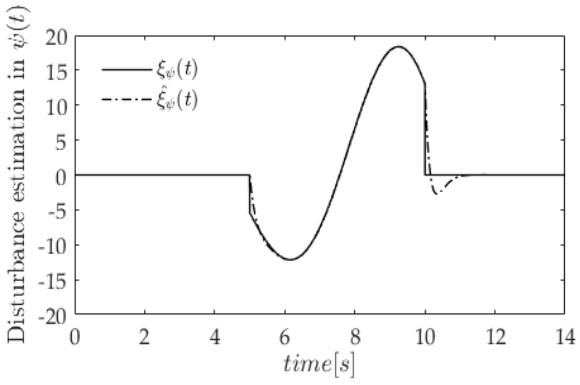


Figure 5. Disturbance estimation of in yaw subsystem.

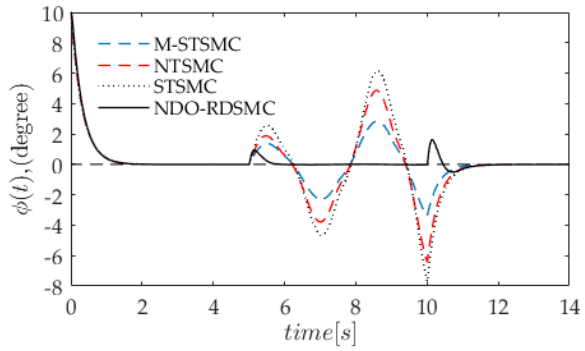


Figure 6. Tracking performance of roll controller.

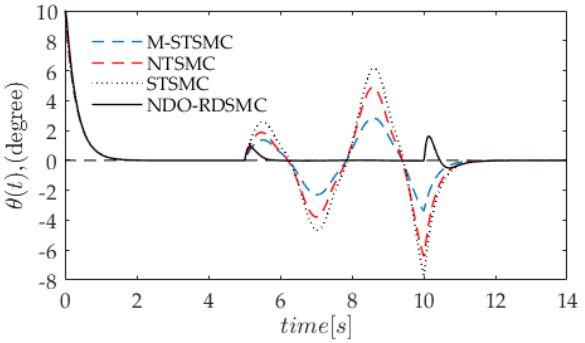


Figure 7. Tracking performance of pitch controller.

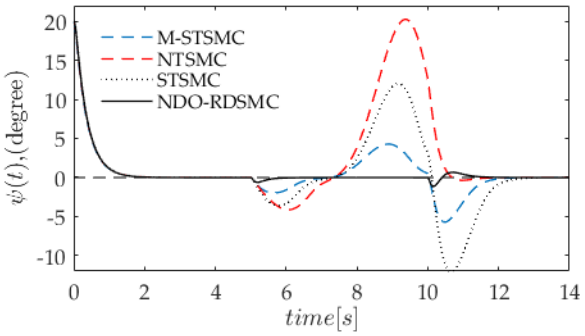


Figure 8. Tracking performance of yaw controller.

In summary, from the results of simulation, obviously all tested studies presented an equally excellent performance under the disappearance of external disturbances, i.e., they gave both fast response and rapid convergence to a steady state. However, the different performance appeared when the external disturbances influence on the dynamics of the vehicle. The existent algorithm i.e. M-STSMC, NTSMC and STSMC could not adapt well to the fast variation of these disturbances, resulting in a large oscillation amplitude and instability of the control system. This problem was solved by the proposed NDO-RDSMC. The proposed method guarantees an excellent tracking performance and superior stability of the UAVs with a rapid response, good adaptation, and no chattering effect.

V. CONCLUSION

In this study, we introduced a robust dynamic sliding mode controller based on nonlinear disturbance observer for a quadcopter unmanned aerial vehicle, and then the robustness and effectiveness of the proposed method was demonstrated through the control performance of attitude. In this algorithm, the external disturbance could be estimated by a nonlinear disturbance observer. Following, a general design procedure of a robust dynamic sliding mode controller combination with the estimated values of perturbation is proposed to compensate for the effect of these disturbances on the system. The strict robustness and efficiency of the proposed method were demonstrated by the simulation resultswith an excellent tracking performance and superior stability of attitude of a quadcopter with a rapid response, good adaptation, and no chattering effect.

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