IOP Conference Series: Materials Science and Engineering

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To cite this article: Ahmed Eltayeb *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **884** 012081

Adaptive Sliding Mode Control Design for the Attitude of the Quadrotor Unmanned Aerial Vehicle (UAV)

Ahmed Eltayeb[1], **Mohd Fua'ad Rahmat**[2], **Mohd Ariffanan Mohd Basri**[3] **and Mohammed A M Mansour**[4]
[1,2,3]Division of Control and Mechatronics Engineering, UniversitiTeknologi Malaysia, 81310 Skudai, Johor, MALAYSIA.
[4]Faculty of Mechanical and Manufacturing Engineering, University Malaysia Pahang, 26600 Pekan, Pahang, MALAYSIA
E-mail: ahmedtayeb5@gmail.com

Abstract. In this article, the adaptive sliding mode controller (ASMC) is developed for the quadrotor attitude subsystem. The proposed ASMC controller aims to reduce/decrease the unwanted chattering phenomena associated with the conventional sliding mode controller, and meanwhile achieving a robust trajectory tracking for the attitude. The stability of the proposed (ASMC) controller has been verified based on Lyapunov stability theorem. The quadrotor UAV model and the performance of the proposed controller have been simulated and tested by simulation using MATLAB/SIMULINK environment. The simulation result is proof that the chattering has been reduced significantly.

1. Introduction

The quadrotor unmanned aerial vehicles (UAV) systems have been getting observable attention from researchers because of its wide applications in civilian and military sectors. The quadrotor classifies as a complex system, due to the high nonlinear dynamics, under-actuated and coupled dynamics, and these challenges must be considered in the controller design stage. There are numerous control techniques applied to the quadrotor, such as PID [1], [2], feedback linearization [3], [4], adaptive control [5], [6], and sliding mode controllers [7].

The SMC control is a nonlinear control technique which drives the system's state trajectories to reach the sliding surface in a limited time and stay on it thereafter. The advantage of the SMC, the robustness against parameter variations and the finite-time to reach the sliding surface [8]–[10]. The main disadvantage of the SMC is the chattering phenomena. There are many proposed methods in the literature to overcome or reducing the chattering effects to some undisturbed limit or rang [11]–[14]. Chattering usually causes many problems such as vibration in the mechanical parts and heating in electronics kits which leads to power consumption. In addition, the discontinuous control signal in SMC may excite high-frequency dynamic of the system neglected in the course of modelling such as unmodeled structural modes, and time delays [15].

In this paper, the proposed ASMC controller has been developed based on Lyapunov theorem. There are two main objectives of the proposed ASMC controller. Firstly, achieving a robust trajectory tracking taking, and secondly reduce the impact of the chattering problem by designing an adaptive gain of switching function, by which the proposed ASMC controller will be able to achieve a robust trajectory tracking and reducing the chattering impact.

2. Quadrotor Dynamics Model

The dynamic equations of quadrotor UAV in 6-degree of freedom (DOFs) are given as follows:

$$
\begin{aligned}
\ddot{x} &= \frac{\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi}{m} u_4 \\
\ddot{y} &= \frac{\cos\phi \sin\theta \cos\psi - \sin\phi \sin\psi}{m} u_4 \\
\ddot{z} &= -g + \frac{\cos\phi \cos\theta}{m} u_4 \\
\ddot{\phi} &= \dot{\theta}\dot{\psi}\frac{I_y - I_z}{I_x} + \dot{\theta}\Omega_d \frac{J_r}{I_x} + \frac{1}{I_x} u_1 \\
\ddot{\theta} &= \dot{\phi}\dot{\psi}\frac{I_z - I_x}{I_y} + \dot{\phi}\Omega_d \frac{J_r}{I_y} + \frac{1}{I_y} u_2 \\
\ddot{\psi} &= \dot{\theta}\dot{\psi}\frac{I_x - I_y}{I_z} + \frac{1}{I_z} u_3
\end{aligned}
\tag{1}
$$

where u_1, u_2, u_3, u_4 are the control inputs, x, y and z denote the position of the quadrotor UAV, while ϕ, θ and ψ represent the quadrotor attitude, roll, pitch and yaw angles, respectively. $J_r$represents the rotor inertia, and I_x, I_y, I_z denote the inertia on x, y, and z axis respectively. $l$is the arm length. $\Omega_d$represents the disturbances.

3. The Adaptive Sliding Mode Control (ASMC) Design

The scope of the ASMC controller design will cover the quadrotor's attitude subsystem dynamics equations only, as follows:

$$
\begin{aligned}
\ddot{\phi} &= a_1\dot{\theta}\dot{\psi} + a_2\dot{\theta}\Omega_d + \frac{1}{I_x} u_1 + \mu_\phi \\
\ddot{\theta} &= a_3\dot{\phi}\dot{\psi} + a_4\dot{\phi}\Omega_d + \frac{1}{I_y} u_2 + \mu_\theta \\
\ddot{\psi} &= a_5\dot{\phi}\dot{\theta} + \frac{1}{I_z} u_3 + \mu_\psi
\end{aligned}
\tag{2}
$$

where,

$$
a_1 = \frac{I_y - I_z}{I_x}, a_2 = \frac{J_r}{I_x}, a_3 = \frac{I_z - I_x}{I_y}, a_4 = \frac{J_r}{I_y}, \text{and } a_5 = \frac{I_x - I_y}{I_z}
$$

And, $\mu_\phi, \mu_\theta, \mu_\psi$ are the lumped uncertainties for ϕ, θ, ψ dynamics, respectively.

Therefore, the control aim is to design ASMC controller to stabilize the attitude error dynamics. The desired attitude given by (ϕ_d,θ_d,ψ_d), while the actual attitude is (ϕ, θ, ψ). The error dynamics is given as follows:

$$
\begin{aligned}
e_\phi &= \phi - \phi_d \\
e_\theta &= \theta - \theta_d \\
e_\psi &= \psi - \psi_d
\end{aligned}
\tag{3}
$$

The proposed ASMC controller has been designed based on the following steps:

Step 1 is to define the tracking errors as in (2).

Step 2 is to select the sliding surface as follows, [10]:

$$s = \left(\frac{d}{dt} + k_x\right)^{n-1} e \tag{4}$$

Thus, the sliding surfaces for attitude angles are

$$\begin{aligned} s_\phi &= \dot{e}_\phi + k_\phi e_\phi \\ s_\theta &= \dot{e}_\theta + k_\theta e_\theta \\ s_\psi &= \dot{e}_\psi + k_\psi e_\psi \end{aligned} \tag{5}$$

where, s_ϕ,s_θ and s_ψ represent the sliding surfaces for roll, pitch and yaw, respectively. While k_ϕ,$\mathrm{k}_\theta$and k_ψ are positive constants.

Step 3 is to apply the sliding mode condition as follows,

$$\dot{s} = -k_1\, sgn(s) - k_2 s \tag{6}$$

Substitute (5) into (6), yields to,

$$\begin{aligned} \ddot{e}_\phi + k_\phi \dot{e}_\phi &= -k_{1_\phi}\, sgn(s_\phi) - k_{2_\phi} s_\phi \\ \ddot{e}_\theta + k_\theta \dot{e}_\theta &= -k_{1_\theta}\, sgn(s_\theta) - k_{2_\theta} s_\theta \\ \ddot{e}_\psi + k_\psi \dot{e}_\psi &= -k_{1_\psi}\, sgn(s_\psi) - k_{2_\psi} s_\psi \end{aligned} \tag{7}$$

Substitute (2) and (2) into (7), yields to,

$$\begin{aligned} &a_1 \dot{\theta}\dot{\psi} + a_2 \dot{\theta}\Omega_d + \frac{1}{I_x} u_1 + \mu_\phi - \ddot{\phi}_d + k_\phi \dot{e}_\phi = -k_{1_\phi}\, sgn(s_\phi) - k_{2_\phi} s_\phi \\ &a_3 \dot{\phi}\dot{\psi} + a_4 \dot{\phi}\Omega_d + \frac{1}{I_y} u_2 + \mu_\theta - \ddot{\theta}_d + k_\theta \dot{e}_\theta = -k_{1_\theta}\, sgn(s_\theta) - k_{2_\theta} s_\theta \\ &a_5 \dot{\phi}\dot{\theta} + \frac{1}{I_z} u_3 + \mu_\psi - \ddot{\psi}_d + k_\psi \dot{e}_\psi = -k_{1_\psi}\, sgn(s_\psi) - k_{2_\psi} s_\psi \end{aligned} \tag{8}$$

where k_{1_ϕ},k_{1_θ},k_{1_ψ}>0and k_{2_ϕ},k_{2_θ},k_{2_ψ}>0 are the SMC control gains.

Step 4 is to cancel the nonlinear terms and uncertainty in the parameters in (8), the control input u_1, u_2, u_3 are selected as follows:

$$\begin{aligned} u_1 &= I_x\left(\ddot{\phi}_d - a_1 \dot{\theta}\dot{\psi} - a_2 \dot{\theta}\Omega_d - k_\phi \dot{e}_\phi + \mu_\phi + U_1\right) \\ u_3 &= I_y\left(\ddot{\theta}_d - a_3 \dot{\phi}\dot{\psi} - a_4 \dot{\phi}\Omega_d - k_\theta \dot{e}_\theta + \mu_\theta + U_2\right) \\ u_4 &= I_z\left(\ddot{\psi}_d - a_5 \dot{\phi}\dot{\theta} - k_\psi \dot{e}_\psi + \mu_\psi + U_3\right) \end{aligned} \tag{9}$$

Substitute (9) into (8) leads to

$$\begin{aligned} \dot{s}_\phi &= U_1 + \zeta_\phi \\ \dot{s}_\theta &= U_2 + \zeta_\theta \\ \dot{s}_\psi &= U_3 + \zeta_\psi \end{aligned} \tag{10}$$

where,

$$\begin{aligned} \zeta_\phi &= I_x \mu_\phi \\ \zeta_\theta &= I_y \mu_\theta \\ \zeta_\psi &= I_z \mu_\psi \end{aligned} \tag{11}$$

Step 5 is to obtain the estimated uncertainty $\zeta_\phi, \zeta_\theta, \zeta_\psi$ based on the following selected Lyapunov functions:

$$\begin{aligned} V_\phi &= \frac{1}{2}s_\phi^2 + \frac{1}{2}\tilde{\zeta}_\phi \gamma_\phi \tilde{\zeta}_\phi \\ V_\theta &= \frac{1}{2}s_\theta^2 + \frac{1}{2}\tilde{\zeta}_\theta \gamma_\theta \tilde{\zeta}_\theta \\ V_\psi &= \frac{1}{2}s_\psi^2 + \frac{1}{2}\tilde{\zeta}_\psi \gamma_\psi \tilde{\zeta}_\psi \end{aligned} \tag{12}$$

where, $\tilde{\zeta}_\phi, \tilde{\zeta}_\theta, \tilde{\zeta}_\psi$ are the error between the actual uncertainty and the estimated uncertainty $\tilde{\zeta}_\phi = \zeta_\phi - \hat{\zeta}_\phi$, $\tilde{\zeta}_\theta = \zeta_\theta - \hat{\zeta}_\theta$, and $\tilde{\zeta}_\psi = \zeta_\psi - \hat{\zeta}_\psi$, while, $\gamma_\phi, \gamma_\theta, and \gamma_\psi$ are positive constant. Thus, by differentiating the both sides of equation (12) yields to:

$$\begin{aligned} \dot{V}_\phi &= s_\phi \dot{s}_\phi + \dot{\tilde{\zeta}}_\phi \gamma_\phi \tilde{\zeta}_\phi \\ \dot{V}_\theta &= s_\theta \dot{s}_\theta + \dot{\tilde{\zeta}}_\theta \gamma_\theta \tilde{\zeta}_\theta \\ \dot{V}_\psi &= s_\psi \dot{s}_\psi + \dot{\tilde{\zeta}}_\psi \gamma_\psi \tilde{\zeta}_\psi \end{aligned} \tag{13}$$

According to (13) the adaption laws are set as follows

$$\begin{aligned} \dot{\hat{\zeta}}_\phi &= \frac{1}{\gamma_\phi} s_\phi \\ \dot{\hat{\zeta}}_\theta &= \frac{1}{\gamma_\theta} s_\theta \\ \dot{\hat{\zeta}}_\psi &= \frac{1}{\gamma_\psi} s_\psi \end{aligned} \tag{14}$$

Thus, from equation (10), the control inputs will be as follows

$$\begin{aligned} U_1 &= -\hat{\zeta}_\phi - k_{1_\phi} sgn(s_\phi) - k_{2_\phi} s_\phi \\ U_2 &= -\hat{\zeta}_\theta - k_{1_\theta} sgn(s_\theta) - k_{2_\theta} s_\theta \\ U_3 &= -\hat{\zeta}_\psi - k_{1_\psi} sgn(s_\psi) - k_{2_\psi} s_\psi \end{aligned} \tag{15}$$

Step 6 is to reduce/eliminate the chattering effects associate with the switching function, the controller parameters k_{1_ϕ}, k_{1_θ}, and k_{1_ψ}which represent the uncertainty bounds can be estimated as follows [16]:

$$\begin{aligned} \dot{\hat{k}}_{1_\phi} &= \beta_\phi |s_\phi| \\ \dot{\hat{k}}_{1_\theta} &= \beta_\theta |s_\theta| \\ \dot{\hat{k}}_{1_\psi} &= \beta_\psi |s_\psi| \end{aligned} \tag{16}$$

where, β_ϕ, β_θ, and β_ψ are positive constants.

4. Simulation Results and Discussion

The Quadrotor mathematical model was simulated using MATLAB/SIMULINK environment, based on (1) and the model parameter are taken from [17], as listed in table 1. While the parameters of the conventional SMC and the proposed ASMC are presented in table 2 and table 3, respectively.

Table 1. Quadrotor's model parameters.

Name	*Parameter*	*Value*	*Unit*
The mass	m	0.650	kg
inertia on x axis	I_x	7.5e-3	kgm^2
inertia on y axis	I_y	7.5e-3	kgm^2
inertia on z axis	I_z	1.3e-2	kgm^2
The thrust coefficient	b	3.13e-5	Ns^2
The drag coefficient	d	7.5e-7	Nms^2
The rotor inertia	J_r	6e-5	kgm^2
The arm length	l	0.23	m

Table 2. SMC controller parameters.

Parameter	$\boldsymbol{\phi}$	$\boldsymbol{\theta}$	$\boldsymbol{\psi}$
k	3	3	3
k_1	30	30	30
k_2	15	15	15

Table 3. Adaptive SMC controller parameters.

Parameter	$\boldsymbol{\phi}$	$\boldsymbol{\theta}$	$\boldsymbol{\psi}$
k	3	3	3
k_2	15	15	15
γ	0.1	0.1	0.1
α	1	1	1

The simulation results proof that the proposed ASMC controller shows a robust and fast response in term of the trajectory tracking for the quadrotor attitude as shown in figure 1 and figure 2 compare to the conventional SMC and Quasi sliding mode control (QSMC) [10]. Figures 3, figure 4 and figure 5 show the chattering effects in the control signals for conventional SMC, QSMC and the proposed ASMC, respectively as can be seen the proposed ASMC showed a satisfactory performance in term of chattering reduction. The adaptive tuned gains for the proposed controller are presented in figure 6.

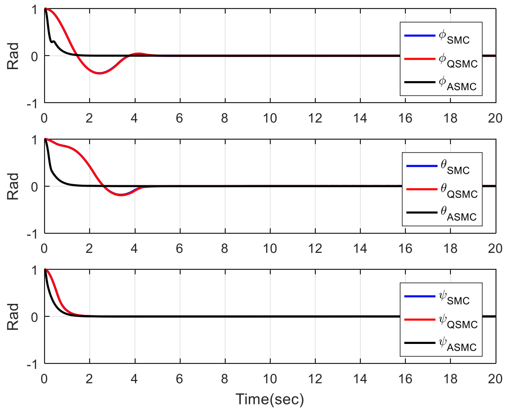

Figure 1. The quadrotor's attitude.

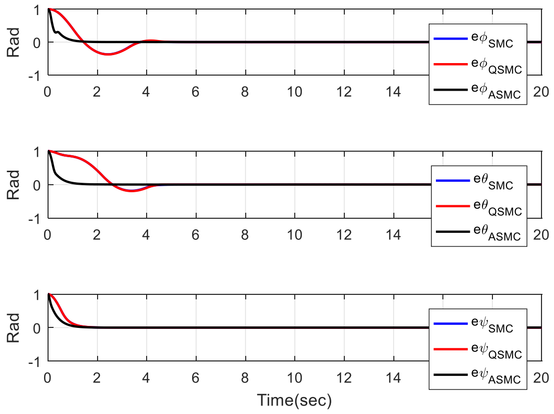

Figure 2. The quadrotor attitude error.

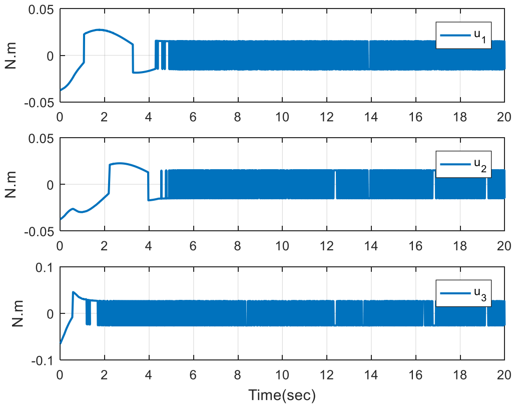

Figure 3. Conventional SMC control signals.

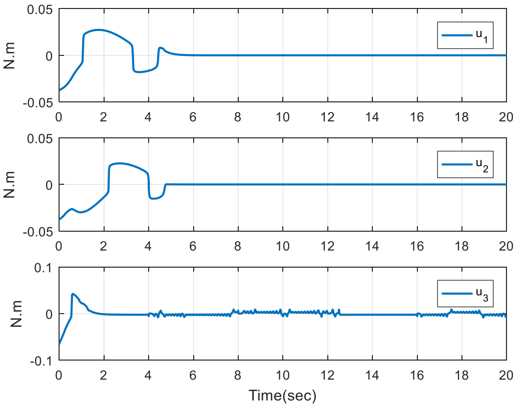

Figure 4. QSMC control signals.

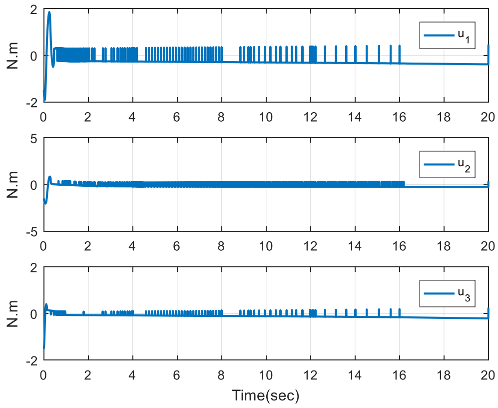

Figure 5. ASMC control signals.

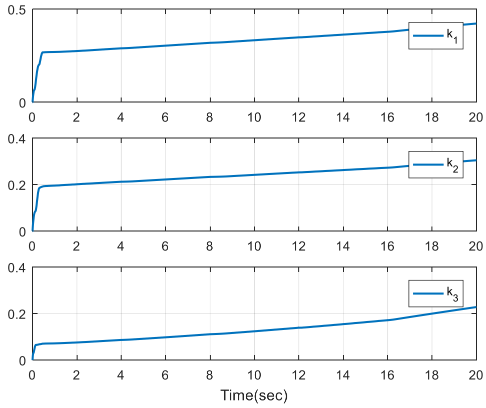

Figure 6. ASMC control adaptive gains.

5. Conclusion and Future work

The proposed adaptive SMC controller has been developed to control and stabilize the quadrotor’s attitude by taking into consideration both a robust trajectory tracking and reduce the chattering impact. The performance of the proposed ASMC controller has been compared with the conventional SMC and QSMC controllers, and the results showed a remarkable improvement, particularly in term of the chattering reduction. The future work has been planned to extend the work to include two major tasks, control the quadrotor UAV in 6 degree-of-freedom (6-DOF), and test the proposed ASMC against the parameter's uncertainty.

Acknowledgement

The author would like to thank for the research grant sponsorship from UTM votenumber Q.J130000.3551.06G80.

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