# Improved Sliding Mode Controller Using Backstepping and Fuzzy Logic for a Quadrotor Aircraft

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***Abstract*—In this work, a new robust nonlinear controller is presented in presence of large external disturbances for a quadrotor aircraft. The controller is based on an improved sliding mode control. The improvement is done by adding two other terms, one is a backstepping synthesis and the other one is a fuzzy logic term in order to reduce the chattering phenomenon and achieve more acceptable performance. The dynamical motion equations are obtained by Euler-Newton formalism. Lyapunov theorem is used to prove the stability of control system. A simulation is carried out to illustrate the effectiveness of the proposed control.**

***Index Terms*—fuzzy logic system, backstepping techniques, sliding mode control, quadrotor.**

## I. Introduction

In practical applications, the UAVs position in space is generally controlled by an operator through a remote-control system, while the attitude can be automatically stabilised via an onboard controller. The attitude controller is an important feature since it allows the vehicle to maintain a desired orientation and, hence, prevents the vehicle from flipping over and crashing [1]. A quadrotor is a dynamic vehicle with four input forces, six output coordinators, highly coupled and unstable dynamics [2], [3]. In the literature, several control algorithms have been proposed to altitude and attitude control problem, linear quadratic regulator (LQR) in [4], PD control in [5], backstepping [6], a command filtered backstepping [7], a direct inverse neural network [8], fuzzy logic based controller [9], proportional integral derivative (PID) [10] and sliding mode control [11]. Sliding mode control is well known for its effectiveness through the theoretical studies against model uncertainties, parameter variations and external disturbances, and has been widely applied to robotics and aerocraft control design [12], [13]. Chattering phenomenon (high frequency of control action) is the major problem associated with sliding mode control (SMC), which is caused by the inappropriate selection of the switching gain. In order to reduce the chattering phenomenon, various methods have been proposed, such as boundary layer, neural network, and fuzzy logic [14], [15], [16]. The fuzzy logic combined with the SMC can be used to achieve better performance [17], [18], [19], [20].

In this paper, a new robust nonlinear controller is developed under large external disturbances for a quadrotor. The proposed controller combines the advantage of the SMC with backstepping synthesis to build backstepping sliding mode controller (BSMC) which itself is also enhanced by a fuzzy logic systems to develop a fuzzy backstepping sliding mode controller (FBSMC). The main idea of the proposed control scheme is the use of fuzzy logic systems to adapt the unknown switching gains to eliminate the chattering phenomenon induced by switching control in BSMC and obtained a good dynamic response.

The paper is organised as follows. In Section II, modeling of quadrotor is presented. In Section III, the FBSMC is designed. Simulations results are depicted in Section IV . Finally, conclusions are given in Section V.

## II. Quadrotor Dynamic Modelling

The quadrotor adopted in this study is introduced in [2], [3] (see Figure 1).

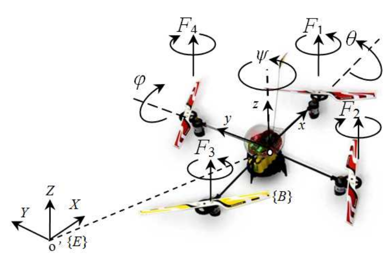


Fig. 1. Quadrotor configuration

Using the Newton-Euler mechanics laws, the dynamic equation of the quadrotor is driven and described as follows:

$$\begin{cases} \ddot{\phi} = 1/I_x \left\{ \dot{\theta}\dot{\psi}\,(I_y - I_z) - K_{fax}\ \dot{\phi}^2 - J_r\overline{\Omega}\dot{\theta} + l\ u_2 + d \right\} \\ \ddot{\theta} = 1/I_y \left\{ \dot{\phi}\dot{\psi}\,(I_z - I_x) - K_{fay}\ \dot{\theta}^2 + J_r\overline{\Omega}\dot{\phi} + l\ u_3 + d \right\} \\ \ddot{\psi} = 1/I_z \left\{ \dot{\theta}\dot{\phi}\,(I_x - I_y) - K_{faz}\ \dot{\psi}^2 +\ u_4 + d \right\} \\ \ddot{x} =\ 1/m \left\{ u_x\, u_1 - K_{ftx}\ \dot{x} + d \right\} \\ \ddot{y} =\ 1/m \left\{ u_y\, u_1 - K_{fty}\ \dot{y} + d \right\} \\ \ddot{z} =\ 1/m \left\{ (Cos\phi\ Cos\theta)\ u_1 - K_{ftz}\ \dot{z} \right\} - g + d \end{cases} \tag{1}$$

where $m$ is the total mass of the quadrotor, $d$ represents the disturbances applied to the quadrotor. $l$ is the distance between the mass centre of the quadrotor and the rotation axis of propeller.
$\overline{\Omega} = (\omega_1 - \omega_2 + \omega_3 - \omega_4)$ is the total gyroscopic torques which affect the quadrotor. $K_{fa} = \text{diag}(K_{fax}, K_{fay}, K_{faz})$ represent the aerodynamics frictions factors. $J_r$ is the total rotational moment of inertia around the propeller axis.
$u_x$ and $u_y$ are two virtual control inputs

$$\begin{cases} u_x = Cos\phi\ Sin\theta\ Cos\psi + Sin\phi\ Sin\psi \\ u_y = Cos\phi\ Sin\theta\ Sin\psi - Sin\phi\ Cos\psi \end{cases} \tag{2}$$

From Eq. (2), it is easy to show that :

$$\begin{cases} \phi_d = \arcsin\ [u_x\ \sin(\psi_d) - u_y\ \cos(\psi_d)] \\ \theta_d = \arcsin\ [\frac{u_x\ \cos(\psi_d) + u_y\ \sin(\psi_d)}{\cos(\phi_d)}] \end{cases} \tag{3}$$

## III. Proposed Controller

The objective is to design a robust tracking controller so that the states vector $X = \{x_1, x_2, ..., x_{12}\} = \{\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}, x, \dot{x}, y, \dot{y}, z, \dot{z}\}^T$ can track a given desired reference $X_d = \{x_{d1}, x_{d2}, ..., x_{d12}\} = \{\phi_d, \dot{\phi}_d, \theta_d, \dot{\theta}_d, \psi_d, \dot{\psi}_d, x_d, \dot{x}_d, y_d, \dot{y}_d, z_d, \dot{z}_d\}^T$ in finite-time, even in presence of large external disturbances in the dynamic model.
Then, the following state representation is obtained:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_1 x_4 x_6 + a_2 x_2^2 + a_3\overline{\Omega}\ x_4 + b_1 u_2 + d \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = a_4 x_2 x_6 + a_5 x_4^2 + a_6\overline{\Omega}\ x_2 + b_2 u_3 + d \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = a_7 x_2 x_4 + a_8 x_6^2 + b_3 u_4 + d \\ \dot{x}_7 = x_8 \\ \dot{x}_8 = a_9 x_8 + u_x u_1/m + d \\ \dot{x}_9 = x_{10} \\ \dot{x}_{10} = a_{10} x_{10} + u_y u_1/m + d \\ \dot{x}_{11} = x_{12} \\ \dot{x}_{12} = a_{11} x_{12} + \cos x_1 \cos x_3\ u_1/m - g_a + d \end{cases} \tag{4}$$

were $U = (u_1, u_2, u_3, u_4)^T \in R^4$ be the control input vectors. with $a1 = (Iy - Iz)/Ix,\quad a2 = -Kfax/Ix,\quad a3 = -Jr/Ix,\quad a4 = (Iz - Ix)/Iy, a5 = -Kfay/Iy, a6 = Jr/Iy,\ a7 = (Ix - Iy)/Iz,\quad a8 = -Kfaz/Iz,\quad a9 = -Kftx/m,\quad a10 = -Kfty/m,\quad a11 = -Kftz/m,\quad b1 = l/Ix,\quad b2 = l/Iy,\quad b3 = 1/Iz.$

### A. Fuzzy backstepping-sliding mode control (attitude control)

Let defined a tracking error between actual and desired yaw as $e_1 = x_1 - \phi_d$. Its time derivative is $\dot{e}_1 = \dot{x}_1 - \dot{\phi}_d = x_2 - \dot{\phi}_d = e_2$.
Step 1. Define sliding surface
The sliding surface is designed as follows [21]:
$s_\phi = (\frac{\partial}{\partial t} + c_1)^{n-1} e_1 = \dot{e}_1 + c_1 e_1$ where $c_1 > 0$.
Step 2. Design control law
The objective of the controller is to enforce the sliding mode into the sliding surface $s_\phi = 0$.
A first Lyapunov function is selected as follows:

$$V_1 = \frac{1}{2} e_1^2 \tag{5}$$

Then, its time derivative is computed as

$$\dot{V}_1 = e_1 \dot{e}_1 = e_1(x_2 - \dot{\phi}_d) \tag{6}$$

In order to realise $\dot{V}_1$ negative definite ($\dot{V}_1 \leq 0$), using backstepping algorithm, we consider the virtual system $x_2 = s_\phi - c_1 e_1 + \dot{\phi}_d$. Then,

$$s_\phi = x_2 + c_1 e_1 - \dot{\phi}_d \tag{7}$$

Using Eqs. (5) and (7), $\dot{V}_1$ can be derived as follows:

$$\dot{V}_1 = e_1 s_\phi - c_1 e_1^2$$

If $s_\phi = 0$ then $\dot{V}_1 \leq 0$. Therefore, the next step is required. A second augmented Lyapunov function is defined as:

$$V_2 = V_1 + \frac{1}{2} s_\phi^2 \tag{8}$$

Therefore,

$$\dot{V}_2 = \dot{V}_1 + s_\phi \dot{s}_\phi \tag{9}$$

From Eq. (7)

$$\begin{aligned} \dot{s}_\phi &= \dot{x}_2 + c_1 \dot{e}_1 - \ddot{\phi}_d \\ &= a_1 x_4 x_6 + a_2 x_2^2 + a_3\overline{\Omega}\ x_4 + b_1 u_2 + d + c_1 \dot{e}_1 - \ddot{\phi}_d \end{aligned}$$

Then, Eq. (9) becomes

$$\begin{aligned} \dot{V}_2 = e_1 s_\phi - c_1 e_1^2 + s_\phi(a_1 x_4 x_6 + a_2 x_2^2 + a_3\overline{\Omega}\ x_4 + \\ b_1 u_2 + d + c_1 \dot{e}_1 - \ddot{\phi}_d) \end{aligned}$$

Assume that the state variables in Eq. (4) are available, and in order to realise $\dot{V}_2$ negative definite, the backstepping-sliding mode control law for roll motion is designed as follows:

$$\begin{aligned} u_2 = \frac{1}{b_1} \big(-k_1\ \text{sign}(s_\phi) - a_1 x_4 x_6 - a_2 x_2^2 - a_3\overline{\Omega}\ \times \\ x_4 - d - c_2 s_\phi - e_1 - c_1 e_2 + \ddot{\phi}_d\big) \end{aligned} \tag{10}$$

where $c_2 \geq 0$, $k_1 \geq D$ are positive real numbers. Therefore,

$$\dot{V}_2 = -\left(c_1 e_1^2 + c_2 s_\phi^2 + s_\phi\ d + k_1\,|s_\phi|\right) \leq 0 \tag{11}$$

which yields, $e_1$ tends to zero and $\dot{e}_1$ tends to zero as $t$ tends to infinity. Therefore, the stability of the closed-loop subsystem along the sliding surface $s_\phi = 0$ is guaranteed. Similar steps can be followed to design BSMC laws for trajectory tracking control of pitch, and yaw angle. The corresponding control laws are designed as follows respectively:

$$u_3 = \frac{1}{b_2}\left(-k_2\ \mathrm{sign}(s_\phi) - a_4 x_2 x_6 - a_5 x_4^2 - a_6\overline{\Omega}x_2 - d - c_4 s_\theta - e_3 - c_3 e_4 + \ddot{\theta}_d\right) \quad (12)$$

$$u_4 = \frac{1}{b_3}\left(-k_3\ \mathrm{sign}(s_\psi) - a_7 x_2 x_4 - a_8 x_6^2 - d - c_6 s_\psi - e_5 - c_5 e_6 + \ddot{\psi}_d\right) \quad (13)$$

where $c_i \geq 0, i = \overline{3,6}$, and $k_2, k_3 \geq D$ are positive real numbers.

The altitude and position controls can be obtained by the similar design procedures

$$u_1 = \frac{m}{\cos x_1\ \cos x_3}\left(-k_6\ \mathrm{sign}(s_z) - a_{11}x_{12} + g - d - c_{12}s_z - e_{11} - c_{11}e_{12} + \ddot{z}_d\right) \quad (14)$$

where $c_i \geq 0, i = \{11, 12\}$, and $k_6 \geq D$ are positive real numbers.

$$u_x = \frac{m}{u_1}\left(-k_4\ \mathrm{sign}(s_x) - a_9 x_8 x_4 - d - c_8 s_x - e_7 - c_7 e_8 + \ddot{x}_d\right) \quad (15)$$

$$u_y = \frac{m}{u_1}\left(-k_5\ \mathrm{sign}(s_y) - a_{10}x_{10} - d - c_{10}s_y - e_9 - c_9 e_{10} + \ddot{y}_d\right) \quad (16)$$

where $c_i \geq 0, i = \overline{7,10}$, and $k_4, k_5 \geq D$ are positive real numbers, $\underline{k} = diag(k_1, ..., k_6)$ and $\underline{c} = diag(k_1, ..., k_{12})$.

The designed BSMC provides an effective robust control approach for quadrotor system Eq. (4). However, the control laws Eqs. (10) to (16) can cause the chattering phenomenon resulting from the use of the `sign` function. In this context, high switching gains $k_i$ will lead to an increase in oscillations of the control input signal, and therefore an excitation of high frequency dynamics. Consequently, a chattering phenomenon will be created. However, increasing the gains causes an increase of the oscillations in input control. Moreover, a decrease of this gains can reduce the chattering phenomenon and improve the tracking performance despite large external disturbances. To achieve more appropriate performance, this gains must be adjusted. This adjustment is based on the distance between the system states and the sliding surface. i.e., when the trajectory of the system state deviates from the sliding surface, the switching gains should be increased in order to reduce chattering and vice versa. This idea can be realised by combining fuzzy logic with backstepping-sliding mode control according to some appropriate fuzzy rules.

For this reason, one-input one-output FLS is designed, in which $(s_i\dot{s}_i)$ as FLS input and switching gain $k_i$ as FLS outputs, were $(i = \overline{1,6})$. Based on the experiences, the type of fuzzy rules is decided as "IF-THEN ".

$$\text{Rule}^{\ l} : If\ (s\dot{s})_i\ is\ A^l_{(s\dot{s})_i}\ THEN\ \Delta k_i\ is\ B^l_i$$

These rules govern the input-output relationship between $s\dot{s}$ and $\hat{k}$ by adopting the Mamdani-type inference engine. A fuzzy logic system with singleton fuzzifier, product-inference rule and centre average defuzzifer is given by the following form:

$$\Delta k_i = \frac{\sum_{l=1}^{N}\ \zeta^l_{ki}\left(\prod_{j=1}^{n}\mu_{A^l_j}(s\dot{s}_j)\right)}{\sum_{l=1}^{N}\left(\prod_{j=1}^{n}\mu_{A^l_j}(s\dot{s}_j)\right)}$$

where $N$ is the total number of fuzzy IF-THEN rules in the rule base, $n$ is the number of system states. $A^l_i$ and $B^l_i$ denote fuzzy sets, $\zeta^l$ is the point at which $\mu_{B^l}$ achieves its maximum value assuming that $\mu_{B^l}(\zeta^l) = 1$.

Using integral method, the supper bound of $\hat{k}_i(t)$ is adapted:

$$\hat{k}_i(t) = G\int_0^t \Delta k_i.dt$$

where $G$ is proportionality coefficient and is decided according to the experiences.

The stability of the proposed control can be proved by the same Lyapunov function Eqs. (5) and (8), replace $k_i$ with $\hat{k}_i$ into control laws Eqs. (10) to (16).

The global diagram of the proposed control is shown in Figure 2.

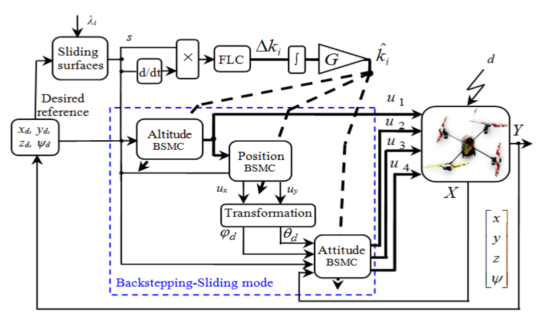


Fig. 2. Control scheme with the hierarchical controller.

## IV. Simulation and Discussions

In this section, numerical simulation is conducted to demonstrate the performance of the developed controllers. The proposed algorithm, applied to the above quadrotor, its nominal parameters are shown in [2], [3].

$X(0) = [0, 1, 0, 2, 0, 2, 1, 0, 1, 2, 0, 2]^T$. The uncertainty which is injected in the structure to verify the robustness of the controller, is a large external disturbance $d(t) = 5e^{\left(\frac{-(t-0.03)^2}{10^2}\right)}.\sin(\pi/4\ \ t).I_{6\times 1}$, where $I_{6\times 1}$ is an identity matrix and it is applied at $t = 5s$. The upper bound of the disturbances is assumed to be $D = max(|d|) = 5$ and $G = 0.01$. The desired trajectory components are chosen to be $x_d = 2$m, $y_d = 2$m, $z_d = 5$m and $\theta_d = 45°$.

First, the system under backstepping sliding mode control law is simulated in order to show its drawback. The controller parameters are selected as follows: $\underline{k} = diag(7, 7, 5, 5, 5, 5)$, $\underline{c} = diag(c_1, ..., c_{12}) = diag(3, 20, 3, 20, 3, 1, 1, 4, 1, 4, 1, 1.5)$. The results obtained for the altitude and attitude tracking control of the quadrotor are given in Figures 3.

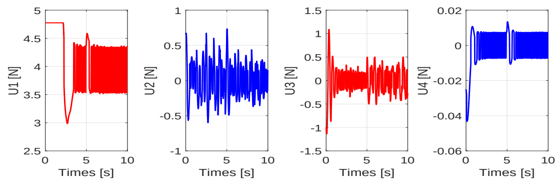


Fig. 3. Control inputs applied to quadrotor using BSMC with disturbances.

It is easy to see that the control performance is not satisfactory due to chattering phenomenon caused by the inappropriate selection of the switching gains. In order to tackle this problem, the smoothing property of fuzzy logic is exploited as seen in previous section. The memberships functions of input and output are chosen as illustrated in Figure 4, in which the following linguistic variables have been used: negative (N), zero (Z), positive (P). The fuzzy base rule of the adopted FLS contains the three rules given in Table I:

TABLE I
FUZZY RULE SET.

| $s\dot{s}$ | N | Z | N |
|---|---|---|---|
| $\Delta k$ | N | Z | N |

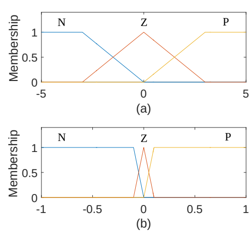


Fig. 4. (a) Input membership functions (b) Output membership functions.

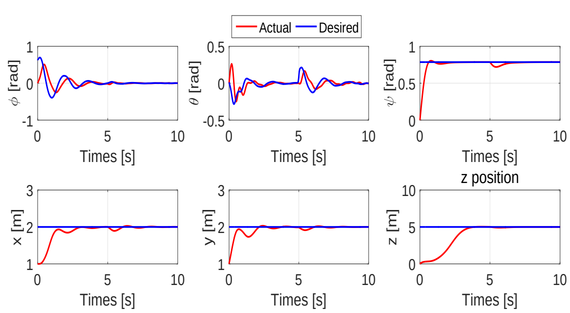


Fig. 5. Outputs system tracking with disturbances.

Figures 5 to 8 show the simulation results corresponding to performance of the fuzzy backstepping-sliding mode controller. Figure 5 illustrates the tracking outputs system in presence of disturbances and shows that the performance and robustness of the proposed controller, under large external

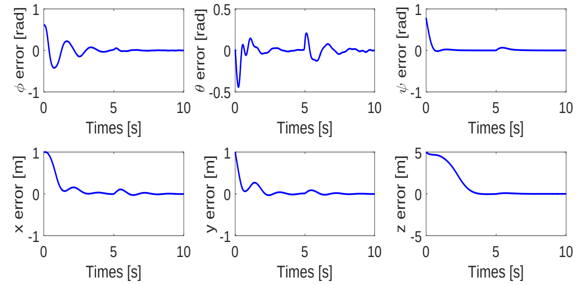


Fig. 6. Outputs system tracking errors with disturbances.

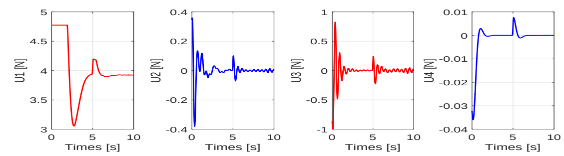


Fig. 7. Control inputs applied to quadrotor using FBSMC with disturbances.

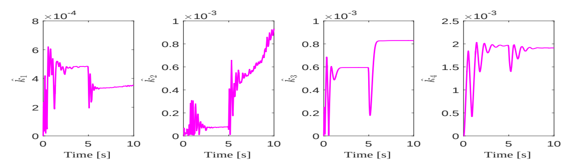


Fig. 8. Evolution of adapted fuzzy switching gains $\hat{k}_i$ with disturbances.

disturbances, are very acceptable. The states converge to their desired ones which show satisfactory tracking during the flight. Figure 6 represents tracking errors which all tend to zero after a finite time with a perfect convergence. The new obtained control inputs are depicted in Figure 7, compared to the old one in Figure 3; one can clearly see that the chattering phenomenon is almost disappeared. Compared to previous studies e.g., [17], [18], [21], [22] and [23], the proposed control approach effectively reduces chattering phenomenon and obtained a good dynamic response. The adapted fuzzy switching gains is depicted in Figure 8, respectively.

## V. CONCLUSION

In this paper, considering large external disturbances, we have proposed a novel robust nonlinear control for quadrotor. The sliding mode control was combined with backstepping techniques to ensure a good robustness. BSMC is enhanced by a fuzzy systems to adapt the unknown switching gains to eliminate the chattering phenomenon induced by switching gain on the conventional BSMC. It is concluded from the simulations that the proposed controller gives good results. This reflects the robustness and performance of the fuzzy backstepping-sliding mode control, which is also confirmed by the tracking errors convergence. Simulation results confirme the ability of the proposed controller to ensure a good tracking and yield superior control performance for quadrotor system against large external disturbances.

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