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FUZZY INTEGRAL SLIDING MODE CONTROLLER FOR AN AUTONOMOUS HELICOPTER

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Abstract

In this paper, we present the result of nonlinear control technique applied to an autonomous quadrotor helicopter called X4-flyer. By using Sliding Mode procedure, we can stabilize the engine in hovering and generate its desired trajectory. Moreover, the Fuzzy PI Sliding Mode controller is the combination of a Fuzzy Integral action and Sliding Mode action that is meant to ensure better performances in term of external load disturbance rejection in the controller system. We studied the robustness of the used controllers in the presence of specific disturbances. In the simulation studies, we considered the wind influence as an external disturbance. This allowed us to validate the effectiveness of the proposed control law.

Keywords: Autonomous Quadrotor Helicopter, Sliding Mode Controller, Inference Fuzzy System, Modelling

1 INTRODUCTION

Recently we have witnesses an increasing interest for mini-aerial vehicles. This is due to the growing number of civil and military applications of UAV (Unmanned Aerial Vehicles). They initially relate to the fields of safety (monitoring of the airspace, of the urban and interurban traffic), the natural risk management (monitoring of the activity of the volcanoes), the environmental protection (measurement of the air pollution, monitoring of the forests), the intervention in hostile sites (radioactive mediums, mine clearance of the grounds without human intervention), the management of the great infrastructures (stoppings, high-voltage lines, pipelines), agriculture (detection and treatment of the cultures) and the catch of air sight in the production of films. All these missions require a powerful control of the apparatus and consequently a precise information on its absolute and/or relative state to its environment. The control of aerial robots requires the knowledge of a dynamic model. These systems, for which the number of control inputs is lower than the number of degrees of freedom are known as under-actuated. Accomplishing these high level missions with UAV systems is critically dependent upon the performance at low level command and control schemes. This fact has made the design, prototyping, implementation and manufacturing of autopilot systems a growing industry. The choice of the autopilot for a UAV system may depend upon the mission statement yet, regardless of the mission statement, the vehicle must be robust enough to cope with the difficulties of the operating environment. The variable structure strategy using the Sliding Mode Controller (SMC) has been the focus of many studies and research for the control of the robot. The goal of the variable structure control is to constrain the system trajectory to the sliding surface via the use of the appropriate switching logic. The SMC can offer good properties, such as insensitivity to parameter variations, external disturbance rejection, and fast dynamics response. However, in SMC, the high frequency chattering phenomenon that results from the discontinuous control action is a severe problem when the state of the system is close to the sliding surface. In various nonlinear control system issues, Fuzzy Logic Controller FLC is recently a popular method to combine with SMC method that can overcome some disadvantages in this issue. Comparing with the classical control theory, the fuzzy control theory does not pay much attention to the stability of system, and the stability of the controlled system cannot be so guaranteed. In fact, the stability is observed based on following two assumptions: First, the input/output data and system parameters must be crisply known. Second, the system has to be known precisely. The FLC is weaker in stability because it lacks a strict mathematics model to demonstrate, although many researches show that it can be stabilized anyway [11], [30]. Nevertheless, the concept of a SMC can be employed to be a basis to ensure the stability of the controller.

The feature of a smooth control action of FLC can be used to overcome the disadvantages of the SMC systems. This is achieved by merging of the FLC with the variable structure of the SMC to form a Fuzzy Sliding Mode Controller [19], [10]. In this hybrid control system, the strength of the SMC lies in its ability to account for modeling imprecision and external disturbances while the FLC provides better damping and reduced chattering.

Modeling and controlling aerial vehicles are the principal preoccupation of our laboratory. The aerial flying engine could not exceed 2kg in mass, a wingspan of 50cm with a 30mn flying-time (see Fig. 1). Within this optic, it can be held that our system belongs to family of mini-UAV. It is an autonomous hovering system, capable of vertical takeoff, landing, lateral motion and quasi-stationary (hover or near hover) flight conditions. Compared to helicopters [1], the four rotors called (X4-flyer) has some advantages [2], [13] and [18]: given that two motors rotate counter clockwise while the other two rotate clockwise, gyroscopic effects and aerodynamic torques tend, in trimmed flight, to cancel. An X4-flyer operates as an omni directional UAV. Vertical motion is controlled by collectively increasing or decreasing the power for all motors. Lateral motion, in x direction or in y direction, is achieved by differentially controlling the motors generating a pitching/rolling motion of the airframe that inclines the collective thrust (producing horizontal forces) and leads to lateral accelerations.

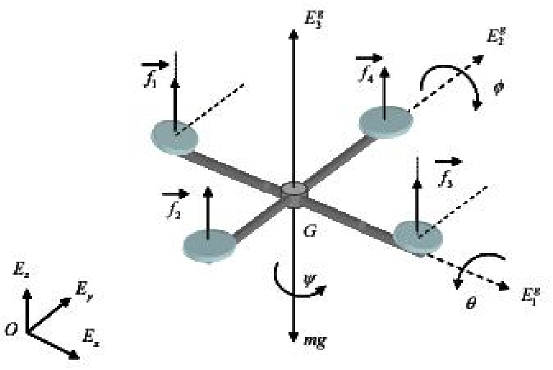

Figure 1: 3D X4-flyer model

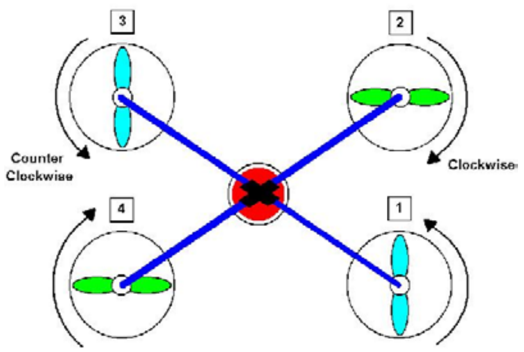

Figure 2: Upper view to the four rotors rotorcraft

Several recent works were completed for the design and control in pilotless aerial vehicles domain such that quadrotor [1], [18] and [24]. Also, related models for controlling the Vertical Take-Off and Landing (VTOL) aircraft are studied by Hauser et al [16]. A model for the dynamic and configuration stabilization of quasi- stationary flight conditions of a four rotors VTOL, based on Newton formalism, was studied by Hamel et al [14] where the dynamic motor effects are incorporating and a bound of perturbing errors was obtained for the coupled system. Castillo et al [9] performed autonomous take-off, hovering and landing control of a four rotors by synthesizing a controller using the Lagrangian model based on the Lyapunov analysis.

The stabilization problem of a four rotors is also studied and tested by Castillo [8] where the nested saturation algorithm is used, the input/output linearization procedure [16], in [6] a proportional integral derivative (PID) controller and a linear quadratic (LQ) controller were implemented and proved capable of regulating the system and application of the theory of flat systems by Beji et al [3]. Mokhtari et al [17] proposed an attempt to apply linear H∞ outer control of helicopter quadrotor with plant uncertainty combined with a robust feedback linearization inner controller. Hanford et al [15] presented a simple closed loop equipped with MEMS (Micro-Electro-Mechanical Systems) sensors and PIC based processing unit. Tayebi and McGilvray [22] proposed a new quaternion-based feedback control scheme for exponential attitude stabilization of a quadrotor. The proposed controller is based upon the compensation of the Coriolis and gyroscopic torques and the use of a PD2 feedback structure, where the proportional action is in terms of the vector quaternion and the two derivative actions are in terms of the airframe angular velocity and the vector quaternion velocity. Bestaoui et al [4] addressed the problem of characterizing maneuvers paths on the group of rigid body motions in 3D for a quadrotor. The role of the trajectory generator is to generate a feasible time trajectory for the UAV. Flight control methods utilizing vision systems are also studied by [23], which exploits the Moiré patterns. Hamel and Mahony [13] proposed a vision based controller which performs visual servo control by positioning a camera onto a fixed target for the hovering of a quadrotor. In [5], [7], authors propose a control-law based on the backstepping and a sliding mode techniques. The developed ideas of control for the XSF (X4 Stationnary Flyer) by the Self-Tunable Fuzzy Inference System (STFIS) controller is presented in [26], [28], [29].

The organization of the paper is as follows: the dynamic model of the vehicle is presented in the next section, the SMC technique is presented in third section. The developed ideas of control for the X4-Flyer by the Fuzzy Integral Sliding Mode Controller is presented to stabilize the vehicle by using the point to point steering stabilization in the fourth section. Motion planning and simulation results are presented in the fifth section. The robustness of the proposed controller is then evaluated in the sixth section. Finally, conclusion and future work are given in the next section.

2 DYNAMIC MODELING

The X4-flyer is a system consisting of four individual electrical fans attached to a rigid cross frame. It is an omni directional Vertical Take-Off and Landing (VTOL) vehicle ideally suited to stationary and quasi- stationary flight conditions. We consider a local reference airframe $\Re_G = \left\{G, E_1^g, E_2^g, E_3^g\right\}$ attached to the center of mass G of the vehicle. The center of the mass is located at the intersection of the two rigid bars, each of them supports two motors. Equipments (controller carts, sensors, etc.) onboard are placed not far from G. The inertial frame is denoted by $\Re_o = \left\{O, E_x, E_y, E_z\right\}$ such that the vertical direction E_z is upwards.

Let the vector $\zeta = (x, y, z)$ denote the position of the center of mass of the airframe in the frame $\Re_O$. While the rotation of the rigid body is determined by a rotation matrix and is defined by $R : R_G \longrightarrow R_O$ where $R \in SO(3)$ is an orthogonal rotation matrix. This matrix is defined by the three Euler angles $\eta = (\psi, \theta, \phi)$. The studied X4-flyer is given in figures (1, 2).

2.1 Translation motion

We consider the translation motion of $\Re_G$ with respect to (wrt) $\Re_O$. The position of the center of mass wrt $\Re_O$ is defined by $\overline{OG} = (x, y, z)^T$, its time derivative gives the velocity wrt $\Re_O$ such that $d\overline{OG}/dt = (\dot{x}, \dot{y}, \dot{z})^T$, the second time derivative permits to get the acceleration: $d^2\overline{OG}/dt^2 = (\ddot{x}, \ddot{y}, \ddot{z})^T$ denoted by $d^2\overrightarrow{OG}/dt^2 = \vec{\gamma}_{G/R_O}$.

By applying the first Newton equation of mechanics, we obtain the following compact expression of the translation motion:

$$m\overrightarrow{\gamma_G} R_O = -mg\overrightarrow{e_z} + R(\psi, \phi, \theta)\overrightarrow{u_3} \tag{1}$$

The vector $\overrightarrow{u_3}$ combines the principal non conservative forces applied to the engine airframe including forces generated by the motors and drag terms. Drag forces and gyroscopic due to motors effects will be not considered in this work. $\overrightarrow{e_z}$ is the unit vector of E_z. The lift (collective) force $\overrightarrow{u_3}$ is the sum of the four forces, such that:

$$\overrightarrow{u_3} = \sum_{i=1}^{4} \overrightarrow{f_i} \tag{2}$$

With $\overrightarrow{f_i} = K_i w_i^2 \overrightarrow{e_3}$ and $\overrightarrow{e_3}$ is the unit vector along E_3^g. The form of the rotation matrix used in Eq. 1 is as follow

$$R = \begin{pmatrix} C_\psi C_\theta & C_\theta S_\psi & -S_\theta \\ S_\phi C_\psi S_\theta - S_\psi C_\phi & S_\theta S_\psi S_\phi + C_\psi C_\phi & C_\theta S_\phi \\ S_\theta C_\psi C_\phi + S_\psi S_\phi & C_\phi S_\theta S_\psi - C_\psi S_\phi & C_\theta C_\phi \end{pmatrix} \tag{3}$$

Where C_θ and S_θ represent $\cos\theta$ and $\sin\theta$ respectively.

One substitutes Eq. 2 into Eq. 1, which leads to the expression,

$$m\overrightarrow{\gamma_G} / R_O = -mg\overrightarrow{e_z} + u_3\, R(\psi, \phi, \theta)\overrightarrow{e_3} \tag{4}$$

2.2 Rotational motion

The rotational motion of the X4-flyer will be defined wrt the local frame but expressed in the inertial frame. According to Classical Mechanics, and knowing the Inertia matrix $I_G = diag(I_{xx}, I_{yy}, I_{zz})$ at the center of the mass.

$$\begin{aligned} \ddot{\theta} &= \frac{1}{I_{xx} C_\phi}\left(\tau_\theta + I_{xx} S_\phi \dot{\phi}\dot{\theta}\right) \\ \ddot{\phi} &= \frac{1}{I_{yy} C_\theta C_\phi}\left(\tau_\phi + I_{yy} S_\phi C_\theta \dot{\phi}^2 + I_{yy} S_\theta C_\phi \dot{\theta}\dot{\phi}\right) \\ \ddot{\psi} &= \frac{\tau_\psi}{I_{zz}} \end{aligned} \tag{5}$$

With the three inputs in torque

$$\begin{aligned} \tau_\theta &= l(f_2 - f_4) \\ \tau_\phi &= l(f_1 - f_3) \\ \tau_\psi &= lk(f_1 - f_2 + f_3 - f_4) \end{aligned} \tag{6}$$

Where l is the distance from G to the rotor i and k is the actuator torque coefficient. The equality from (5) is ensured, meaning that

$$\ddot{\eta} = \Pi_G(\eta)^{-1}\left[\tau - \dot{\Pi}_G(\eta)\dot{\eta}\right] \tag{7}$$

With $\tau = (\tau_\theta, \tau_\phi, \tau_\psi)^T$ as auxiliary inputs.

And

$$\Pi_G(\eta) = \begin{pmatrix} I_{xx}C_\phi & 0 & 0 \\ 0 & I_{yy}C_\phi C_\theta & 0 \\ 0 & 0 & I_{zz} \end{pmatrix} \tag{8}$$

As a first step, the model given above can be input/output linearized by the following decoupling feedback laws.

$$\begin{aligned} \tau_\theta &= -I_{xx}S_\phi\dot{\phi}\dot{\theta} + I_{xx}C_\phi u_4 \\ \tau_\phi &= -I_{yy}S_\phi C_\theta\dot{\phi}^2 - I_{yy}S_\theta C_\phi\dot{\theta}\dot{\phi} + I_{yy}C_\theta C_\phi u_5 \\ \tau_\psi &= I_{zz}u_6 \end{aligned} \tag{9}$$

And the decoupled dynamic model of rotation can be written as:

$$\ddot{\eta} = u \tag{10}$$

With $u = (u_4\, u_5\, u_6)^T$

Using Eq. (4) and Eq. (10), the dynamic of the system is defined by:

$$\begin{aligned} m\ddot{x} &= -S_\theta u_3 \\ m\ddot{y} &= C_\theta S_\phi u_3 \\ m\ddot{z} &= C_\theta C_\phi u_3 - mg \\ \ddot{\theta} &= u_4 \\ \ddot{\phi} &= u_5 \\ \ddot{\psi} &= u_6 \end{aligned} \tag{11}$$

The vectors u_3, u_4, u_5 and u_6 combines the principal non conservative forces applied to the engine airframe including forces generated by the motors and drag terms.

3 SLIDING MODE CONTROLLER

A sliding mode controller is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map the plant state to a control surface, and the switching among different functions is determined by the plant state that is represented basically by a switching function.

Here we assume that $u(t)$ is the input to the system. The following is a possible choice of the structure of a sliding mode controller:

$$u = -k\,\mathrm{sgn}(s) + u_{eq} \tag{12}$$

Where u_{eq} is called the equivalent control which is used when the system state is in the sliding mode. The gain k is a constant and it is the maximal value of the controller output.

s is called switching function because the control action switches its sign on the two sides of the switching surface $s = 0$. s is defined as:

$$s = \left(\frac{\partial}{\partial t} + \lambda\right)^{r-1} e \tag{13}$$

Where $e = x - x_{ref}$ and x_{ref} is the desired state. r is the degrees of the sliding surface, λ is a constant and $\text{sgn}(s)$ is a sign function, which is defined as:

$$\text{sgn}(s) = \begin{cases} -1 & s < 0 \\ 1 & s > 0 \end{cases} \tag{14}$$

The control strategy adopted here will guarantee the system trajectories to move toward and stay on the sliding surface $s = 0$ from any initial condition if the following condition meets:

$$s\dot{s} < 0 \tag{15}$$

Using a sign function often causes chattering in practice. One possible solution is to introduce a boundary layer around the switch surface:

$$u = u_n + u_{eq} \tag{16}$$

Where: $u_n = -k\, sat\left(s/\sigma\right)$ and constant factor σ defines the thickness of the boundary layer. $sat\left(s/\sigma\right)$ is a saturation function that is define as [12]:

$$sat\left(s/\sigma\right) = \begin{cases} s/\sigma & if \left|\left(s/\sigma\right)\right| \le 1 \\ \text{sgn}\left(s/\sigma\right) & if \left|\left(s/\sigma\right)\right| > 1 \end{cases} \tag{17}$$

3.1 Sliding Mode Control of the Linear Translations

3.1.1 Altitude Control: The altitude, can be controlled by the SMC controller. With through the equation of the following movement equation with respect to (z).

$$m\ddot{z} = C_\theta C_\phi u_3 - mg \tag{18}$$

The surface (13) is deduced from the [20], [21] here the degrees of the sliding surface r equal to 2 so that one obtain:

$$s(z) = \dot{e}_z + \lambda_z e_z \tag{19}$$

$$e_z = z - z_{ref} \tag{20}$$

$$\dot{e}_z = \dot{z} - \dot{z}_{ref} \tag{21}$$

As result the surface derivative is:

$$\dot{s}(z) = \ddot{e}_z + \lambda_z \dot{e}_z \tag{22}$$

$$\ddot{e}_z = \ddot{z} - \ddot{z}_{ref} \tag{23}$$

When the sliding mode occurs, the surface *s(z)* became null also its derivative. That gives the control:

$$u_{eq} = \frac{m}{C_\theta C_\phi}\left(g + \ddot{z}_{ref} - \lambda_z\left(\dot{z} - \dot{z}_{ref}\right)\right) \tag{24}$$

During de convergence mode we have to satisfies the condition $s(z)\dot{s}(z) < 0$ by choosing

$$u_n = -k_z sat(s(z)) \tag{25}$$

So that, the output command of the altitude is given as follows:

$$u_3 = \frac{m}{C_\theta C_\phi}\left(g + \ddot{z}_{ref} - \lambda_z\left(\dot{z} - \dot{z}_{ref}\right)\right) - k_z sat(s(z)) \tag{26}$$

3.1.2 Linear x and y Motion Control: From the model (9) one can see that the motion through the axes *x* and *y* depends on u_3. In fact u_3 is the total thrust vector oriented to obtain the desired linear motion. If we considered $u_x = S_\theta$ and $u_y = C_\theta S_\phi$ the orientations of the vector u_3 responsible for the motion through x and y axis respectively, we can then extract the roll and pitch angle necessary to compute the control inputs u_x and u_y.

$$\begin{cases} u_x = \dfrac{m}{u_3}\left(\lambda_x\left(\dot{x} - \dot{x}_{ref}\right) - \ddot{x}_{ref} \right) - k_x sat(s(x)) \\ u_y = \dfrac{m}{u_3}\left(-\lambda_y\left(\dot{y} - \dot{y}_{ref}\right) + \ddot{y}_{ref} \right) - k_y sat(s(y)) \end{cases} \tag{27}$$

3.2 Sliding Mode Control of the Rotations Subsystem

3.2.1 Roll Control ϕ*:* The SMC is applied to roll angle, in such a way to obtain simple surface. Figure 3, shows the proposed control scheme in a cascade form.

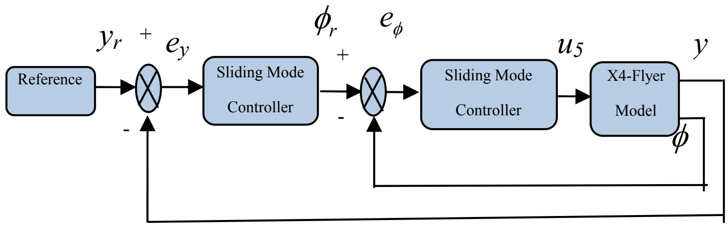

Figure 3: Sliding Mode Control of the drone

Here the degrees of the sliding surface r equal to 2 so that one can obtain:

$$s(\phi) = \dot{e}_\phi + \lambda_\phi e_\phi \tag{28}$$

$$e_\phi = \phi - \phi_{ref} \tag{29}$$

$$\dot{e}_\phi = \dot{\phi} - \dot{\phi}_{ref} \tag{30}$$

As result the surface derivative is:

$$\dot{s}(\phi) = \ddot{e}_\phi + \lambda_\phi \dot{e}_\phi \tag{31}$$

$$\ddot{e}_\phi = \ddot{\phi} - \ddot{\phi}_{ref} \tag{32}$$

When the sliding mode occurs, the surface $s(\phi)$ becomes null as well as its derivative. That gives the following equivalent control input:

$$u_{eq} = \ddot{\phi}_{ref} - \lambda_\phi\left(\dot{\phi} - \dot{\phi}_{ref} \right) \tag{33}$$

Where

$$u_5 = u_{eq} + u_n \tag{34}$$

During the convergence mode we have to satisfy the condition $s(\phi)\dot{s}(\phi) < 0$ by choosing

$$u_n = -k_\phi sat(s(\phi)) \tag{35}$$

This leads to a sliding mode controller for ϕ control given by

$$u_5 = \ddot{\phi}_{ref} - \lambda_\phi\left(\dot{\phi} - \dot{\phi}_{ref}\right) - k_\phi sat(s(\phi)) \tag{36}$$

3.2.2 Pitch and Yaw Control (θ, ψ): The same steps are followed to extracted in order to extract

$$u_4 = \ddot{\theta}_{ref} - \lambda_\theta(\dot{\theta} - \dot{\theta}_{ref}) - k_\theta sat(s(\theta)) \quad (37)$$

$$u_6 = \ddot{\psi}_{ref} - \lambda_\psi(\dot{\psi} - \dot{\psi}_{ref}) - k_\psi sat(s(\psi)) \quad (38)$$

3.3 Integral Sliding Mode Motion Control for z Direction

We propose to add the Integral action (PI-SM) in the surface which is given by

$$s(z) = \dot{e}_z + \lambda_z e_z + k_1 x_1 \quad (39)$$

Where $x_1 = \int_0^t e_z(\tau)d\tau$ is the integral action which can ensure the convergence of the tracking error converges to zero.

With

$$e_z = z - z_{ref} \quad (40)$$

$$\dot{e}_z = \dot{z} - \dot{z}_{ref} \quad 41)$$

As result the surface derivative is:

$$\dot{s}(z) = \ddot{e}_z + \lambda_z \dot{e}_z + k_1 e_z \quad (42)$$

$$\ddot{e}_z = \ddot{z} - \ddot{z}_{ref} \quad (43)$$

When the sliding mode occurs, the surface s(z) became null also its derivative. That gives the control:

$$u_{eq} = \frac{m}{C_\theta C_\phi}\left(g + \ddot{z}_{ref} - \lambda_z(\dot{z} - \dot{z}_{ref}) - k_1(z - z_{ref})\right)$$

During the convergence mode we have to satisfies the condition $s(z)\dot{s}(z) < 0$ by choosing

$$u_n = -k_z sat(s(z)) \quad (44)$$

So that, the output command of the altitude is given as follows:

$$u_3 = \frac{m}{C_\theta C_\phi}\left(g + \ddot{z}_{ref} - \lambda_z(\dot{z} - \dot{z}_{ref}) - k_1(z - z_{ref})\right) - k_z sat(s(z)) \quad (45)$$

3.4 Fuzzy Integral Sliding Mode Motion Control for z Direction

In this section, the Fuzzy PI Sliding Mode controller is proposed, in which the integral action is replaced by an inference fuzzy system to eliminate the static error affecting positively the robustness of the overall controlled system. Figure 4, shows the proposed control for z direction.

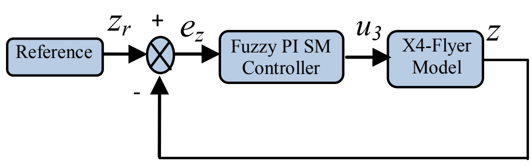

Figure 4: Fuzzy Integral Sliding Mode Controller

The shape of the used membership functions is chosen to be triangular and fixed in order to extract and represent the knowledge from the final results easily. To deduce the truth value, we use the MIN operator for the composition of the input variables.
The universes of discourse are normalized and shared into five fuzzy subsets for all displacement. The linguistic labels are defined as follows:
NB: *Negative Big*, NS: *Negative Small*, Z: *approximately Zero*, PS: *Positive Small* and PB: *Positive Big*

$$R_i : if\ e\ is\ A_i\ and\ de\ is\ B_i\ then\ du\ is\ C_i, \qquad i = 1,\cdots,5 \tag{46}$$

Where A_i, B_i and C_i are triangle shaped fuzzy number, see Fig. 5 and Fig. 6.

The results of the simulation are reported in the table Table 1 for z displacement.

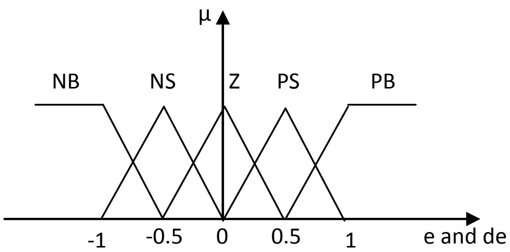

Figure 5: The input membership function of the Fuzzy PI SM Controller

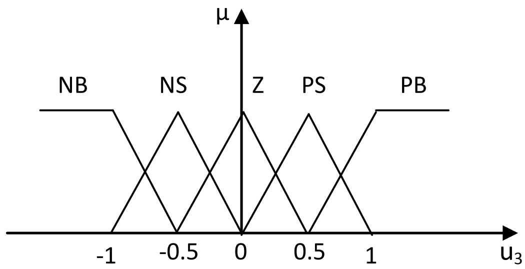

Figure 6: The output membership function of the Fuzzy PI SM Controller

The same observations are found according to the two directions x and y.

Table 1: Expertise linguistic table

de/e	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PB
PB	Z	PS	PS	PB	PB

4 SIMULATIONS RESULTS

The drone is tested in simulation in order to validate some motion planning algorithm considering the proposed sliding mode control laws. We have considered a total mass equal to m = 2kg. We solve the tracking control problem using the point to point steering stabilization see [25], [27] for more details.
Figure 7, shows the tracking of the desired trajectory by the real one and the evolution of the quadrotor and its stabilization in 3D displacement for the straight corner.
Figure 8, illustrates the controlled positions xyz using sliding mode controller where u_3, u_4 and u_5, denote the command signals for z, x and y directions respectively. Note that the input $u_3 = mg$ at the equilibrium state is always verified. The inputs u_4 and u_5 tend to zero after having carried out the desired orientation of the vehicle.

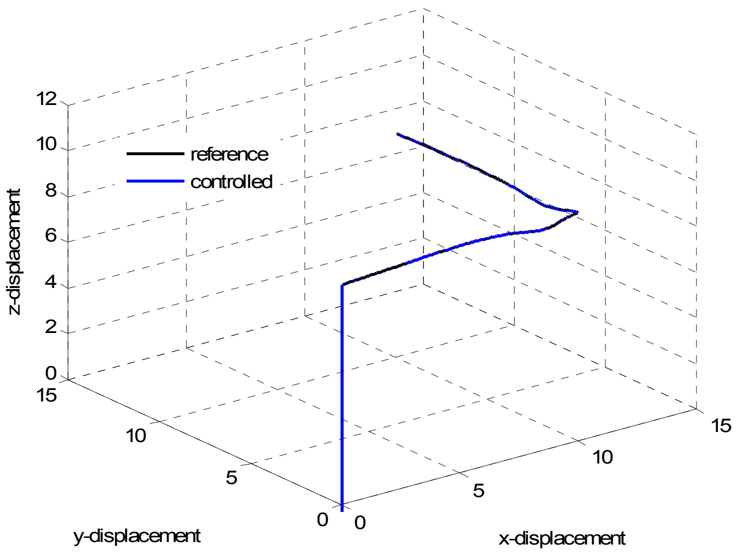

Figure 7: Realization of straight corners

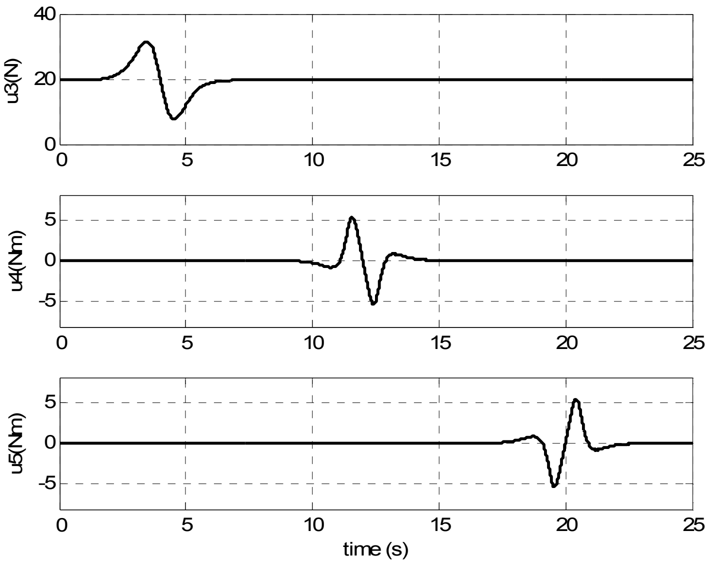

Figure 8: The inputs u_3, u_4 and u_5 for the *xyz* displacement

Figure 9, shows the displacement errors according to all the directions. It is noticed that the error thus tends to zero toward the desired positions.

On the Fig. 10, we notice that the angles θ and ϕ control the engine for displacements along the axes x and y. These angles tend to the zero value.

Figure 11, Figure 12 and Figure 13, show the tracking of desired trajectory by the real one and the evolution of the quadrotor and its stabilization in 3D displacement for the arc, circle, cone and helical trajectories respectively to evaluate the performance of the proposed control. From these figures we can see clearly better performances in trajectory tracking. These results confirm the good results achieved by the proposed controller and its superiority.

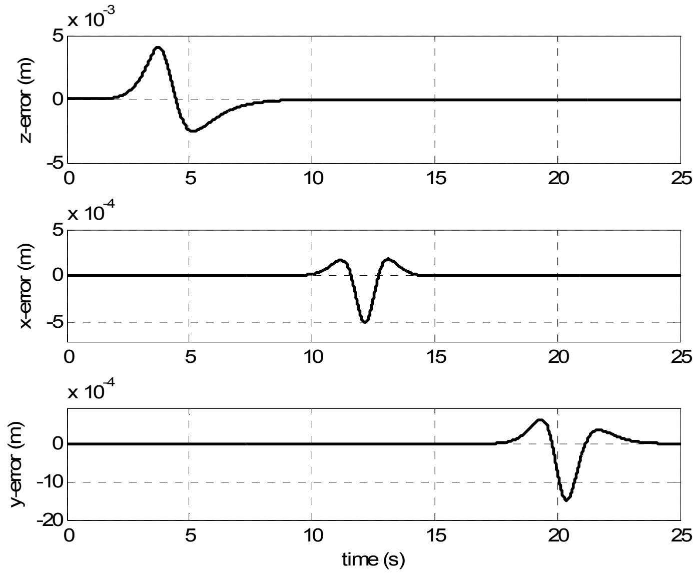

Figure 9: Displacement errors according to the model three directions

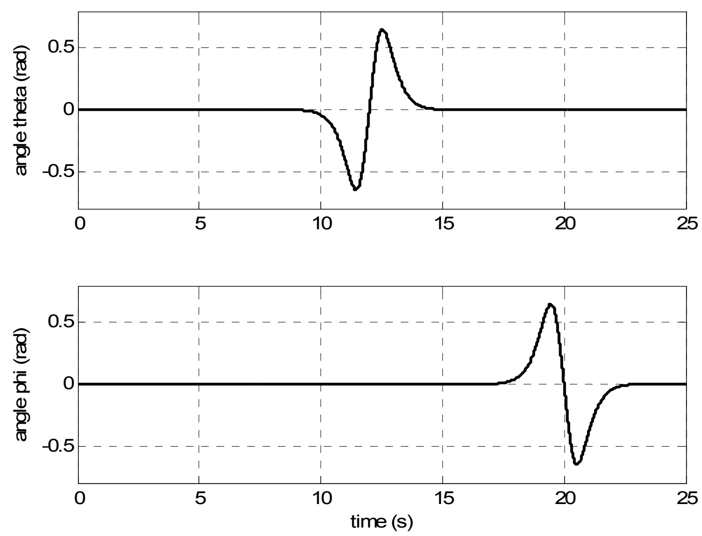

Figure 10: The pitch (theta) and the roll (phi)

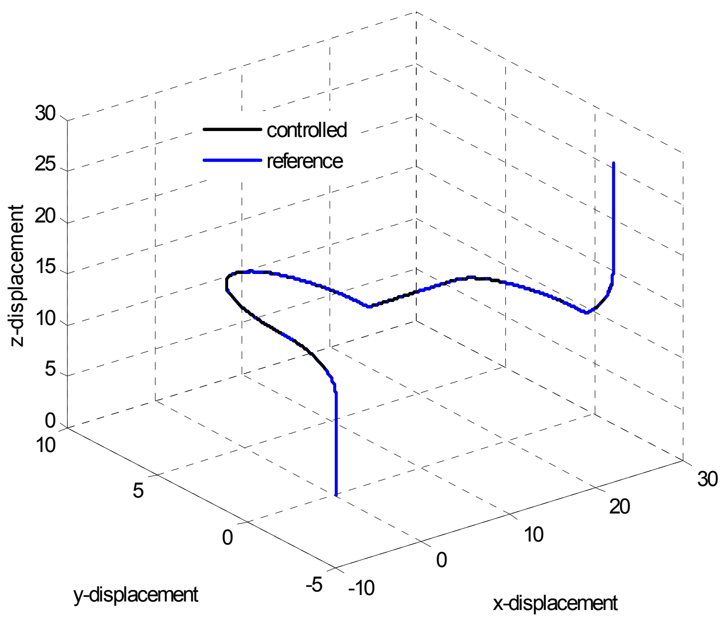

Figure 11: Realization of a round and arc corners

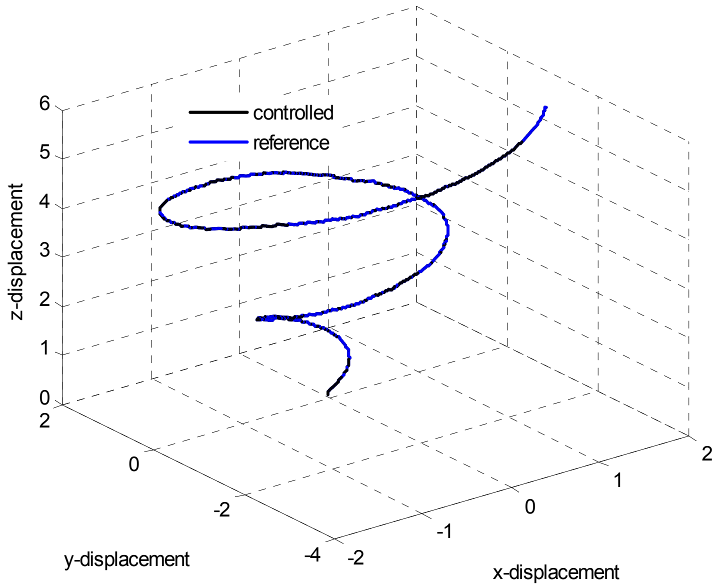

Figure 12: Realization of a cone corners

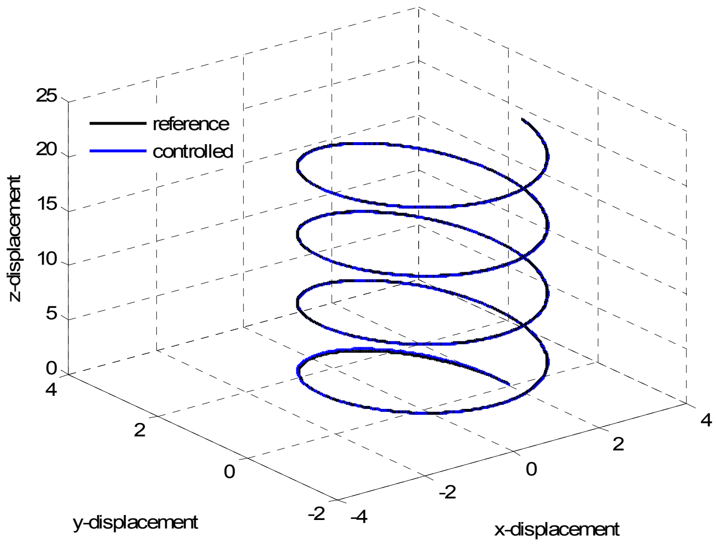

Figure 13: Realization of Helical corners

5 CONTROLLERS ROBUSTNESS

The robustness study was realized in simulations taking into account disturbances considered as wind influence. We considered two cases: in the first one the drag force is equal to $F_{dg} = 3N$ and $6N$ in the second case for both SMC and Fuzzy PI-SM controller along the z direction.

The Figure 14, present the simulation results in the case of a drag force of $F_{dg} = 3N$ according to the z displacement. In order to validate the control law developed we implemented a disturbance force at $t = 8s$ and we test the controllers.

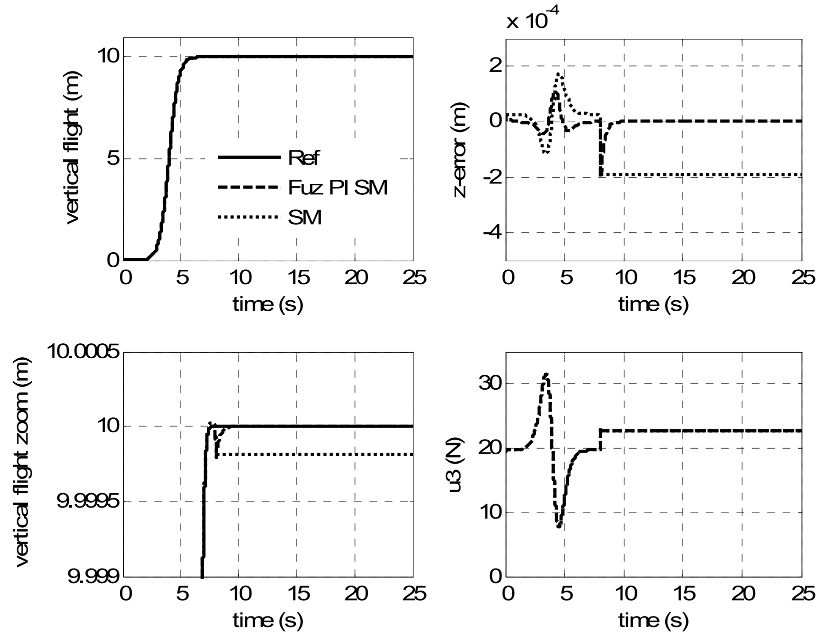

Figure 14: Vertical flight with disturbances (Fdg = 3N) for SMC and Fuzzy PI-SMC

To see the behavior of two controllers according to wind influence, the Fig. 14 and Fig. 15, show the allure vertical flight for both controllers. It is noticed that the Fuzzy PI-MC controller gives good results compared to the SMC controller.

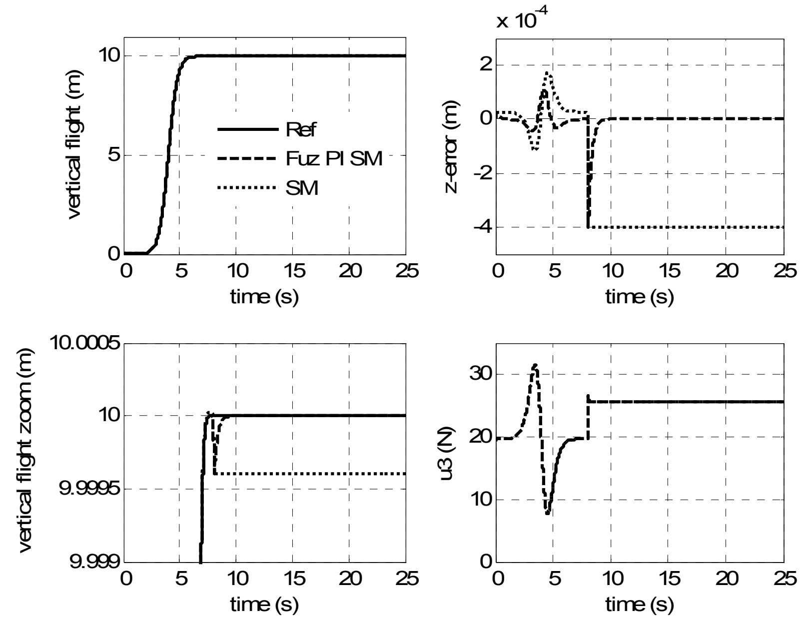

Figure 15: Vertical flight with disturbances (Fdg = 6N) for SMC and Fuzzy PI-SMC

6 CONCLUSION

In this paper, dynamics of a four rotors helicopter are studied and controlled using the Fuzzy Integral Sliding Mode technique. The Stabilizing/tracking control problem for the three decoupled displacements of an X4-flyer has been considered. The objectives were to test the capability of the engine to fly with straight, circle and helical reference trajectories. This technique was successfully applied and tested by computer simulations.

A comparison between the Fuzzy Integral Sliding Mode controller and Sliding Mode controller shows the validity of the proposed technique. An analysis of the Fuzzy Integral Sliding Mode and Sliding Mode controllers and their robustness regarding disturbance shows the effectiveness of the proposed controllers.

Future works will essentially investigate the real time implementation of this technique. A realization of a control system based on engine sensors information is considered. Their performances will be highlighted compared to the previously used techniques.

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