Noname manuscript No.
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Passive fault tolerant control of a new reconfigurable quadrotor

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Received: date / Accepted: date

Abstract The purpose of this paper is to improve the control performance of a new reconfigurable quadrotor subject to change of configuration and under actuator Loss of Effectiveness (LOE) using Integral Sliding Mode Controller (ISMC). First, we present the design of the UAV which is capable of folding its arms instantaneously during the flight which result variation in its different parameters such as Center of Gravity (CoG), inertia and control matrix. Then, the ISMC controller based Passive Fault Tolerant Control (PFTC) is designed to control and stabilize the position and the attitude of the UAV in some possible configurations and under actuator fault conditions. The four servomotors used to rotate the quadrotor arms are controlled by PID controller. Finlay, we present simulation results using Matlab/Simulink environment which demonstrate the effectiveness and the robustness of the ISMC-PFTC controller compared to the regular SMC one.

Keywords Reconfigurable quadrotor · Foldable arms · Integral sliding mode control · Passive fault tolerant control · Loss of effectiveness

1 Introduction

In the last two decades, many prototypes of multirotors Unmanned Aerial Vehicles (UAVs) have been designed and constructed to deal with the new challenges and ensure good performance in more complex environments of civilian and military applications.

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The reconfigurable quadrotors is a special class of multirotors, which has been developed and studied recently. These prototypes have the advantage of adaptive morphology by changing the configuration during the flight in order to execute specific tasks in some specific environments [1],[2] such as passing through small and narrow spaces, inspecting dangerous places, search and rescue, obstacles avoidance and fault tolerant control.
The control of reconfigurable quadrotors remains a major challenge because of the complexity of these systems. Many works have been done in order to deal with control problems of these systems subject to changes in geometric properties, with or without taking into account dynamic changes of the Center of Gravity (CoG) and variation of inertia matrix. Authors in reference [3] used an adaptive PID controller to control a foldable quadrotor with a single servomotor. In paper [4], authors have developed a multi-link foldable quadrotor controller based on Linear Quadratic Integral (LQI) for attitude and altitude control and PID for the position. An adaptive feedback linearization is proposed in [5] which compensates for the dynamic changes of the quadrotor due to the displacement of the CoG. The authors of [6] used an adaptive controller based on a Model Reference Adaptive Control.
Fault Tolerant Control for conventional quadrotors were the subject of many proposed studies in the literature, the methods may be grouped into passive and active FTCs [7]. Authors in reference [8] proposed two passive fault tolerant controllers based on sliding mode theory for AscTec Pelican quadrotor; the regular SMC and the cascaded SMC. Mallavalli et al in [9] proposed a passive FTC approach based on adaptive Integral Terminal SMC to handle unmatched perturbations and fault uncertainties. In paper [10], Li et al designed passive and active sliding mode fault tolerant controllers developed

using augmented sliding mode techniques and by combining integral action in the SMC design. Guiatni et al in [11] proposed an active FTC where the diagnosis system is based on the motors speed measurements.
We need a powerful controller able to overcome the changing in the system configuration. In this paper, we choose the sliding mode control strategy because it has the property of robustness to disturbances, aerodynamic changes and actuator faulty situation. So, we consider the control of our reconfigurable quadrotor using Integral Sliding Mode Controller and taking into account the changes in geometry properties (variation of the CoG and the inertia matrix) and subject to partial loss of effectiveness in one actuator. This method can handle predefined small faults and it is tuned with fixed gains in both fault free and faulty situations.
The rest of the paper is organized as follows: in section 2, the reconfigurable quadrotor design and its model in cross configuration are presented. Section 3 details the control strategy using an augmented sliding surface technique and by combining the integral action in the SMC design. Simulation results are then shown in section 4. Finally, conclusions are drawn.

2 RECONFIGURABLE QUADROTOR MODELING

2.1 System Description

The design of our reconfigurable quadrotor is based on the standard DJI F450 quadcopter, which is modified to make the arms of the prototype rotatable around the central body using four fast servomotors. It is composed

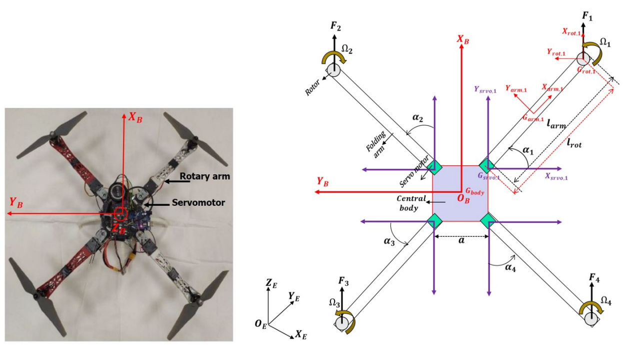

Fig. 1 The reconfigurable quadrotor with foldable arms and its schematic.

of a rectangular central body of width a and mass m_0, four rotors numbered 1,2,3 and 4 of mass $m_{r,i}$, mounted on four arms of length $l_{arm,i}$ and mass $m_{a,i}$, these arms are attached to the central body by four rotation servomotors of mass $m_{s,i}$. The axes of rotation of both rotors and arms are parallel to Z_B axis, the two opposite rotors (2,4) spin in the clockwise direction and the others (1,3) spin in the anticlockwise direction, as shown in Figure 1.
In Figure 2, we can see some possible configuration of our reconfigurable quadrotor, so the four arms can rotate around the central body independently by changing the angles $\alpha_i (i = 1, 2, 3, 4)$.

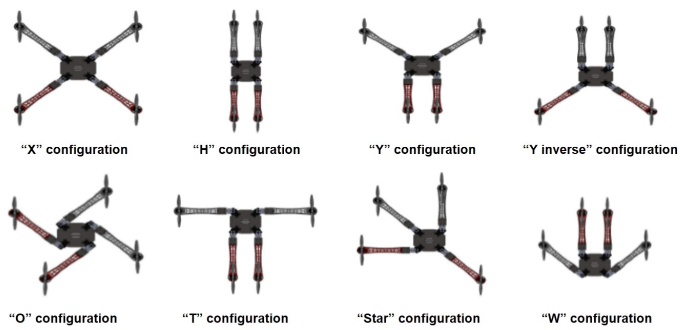

Fig. 2 The reconfigurable quadrotor in some possible configurations.

2.2 Modeling and Dynamics

The modeling of the vehicle described above is based on multi-body modeling approach.
We define the following vectors:
$\overrightarrow{O_B G} = \left[x_G \; y_G \; z_G\right]^T$, the global CoG. $\overrightarrow{O_B G_b} = \left[x_B \; y_B \; z_B\right]^T$, the CoG of the central body. $\overrightarrow{O_B G_{a,i}} = \left[x_{a,i} \; y_{a,i} \; z_{a,i}\right]^T$, the CoG of the i^{th} fixed arm. $\overrightarrow{O_B G_{r,i}} = \left[x_{r,i} \; y_{r,i} \; z_{r,i}\right]^T$, the CoG of the i^{th}rotor.
The coordinates of the centers of gravity of the four arms and the four rotors are given as follows:

$$\left\{\begin{array}{l} x_{a,1} = \frac{a}{2} + \frac{l_{arm,1}}{2} s_{\alpha_1}, \; y_{a,1} = -\frac{a}{2} - \frac{l_{arm,1}}{2} c_{\alpha_1} \\ x_{a,2} = \frac{a}{2} + \frac{l_{arm,2}}{2} c_{\alpha 2}, \; y_{a,2} = \frac{a}{2} + \frac{l_{arm,2}}{2} s_{\alpha 2} \\ x_{a,3} = -\frac{a}{2} - \frac{l_{arm,3}}{2} s_{\alpha 3}, \; y_{a,3} = \frac{a}{2} + \frac{l_{arm,3}}{2} c_{\alpha_3} \\ x_{a,4} = -\frac{a}{2} - \frac{l_{arm,4}}{2} c_{\alpha 4}, \; y_{a,4} = -\frac{a}{2} - \frac{l_{arm,4}}{2} s_{\alpha_4} \\ x_{r,1} = \frac{a}{2} + l_{rot,1} s_{\alpha_1}, \; y_{r,1} = -\frac{a}{2} - l_{rot,1} c_{\alpha_1} \\ x_{r,2} = \frac{a}{2} + l_{rot,2} c_{\alpha 2}, \; y_{r,2} = \frac{a}{2} + l_{rot,2} s_{\alpha 2} \\ x_{r,3} = -\frac{a}{2} - l_{rot,3} s_{\alpha 3}, \; y_{r,3} = \frac{a}{2} + l_{rot,3} c_{\alpha_3} \\ x_{r,4} = -\frac{a}{2} - l_{rot,4} c_{\alpha 4}, \; y_{r,4} = -\frac{a}{2} - l_{rot,4} s_{\alpha_4} \end{array}\right. \tag{1}$$

$c_{(.)}$ and $s_{(.)}$ are abbreviations for cos(.) and sin(.) respectively.
The global CoG of the system, which depends on the rotation angles α_i is:

$$\left\{\begin{array}{l} x_G = \frac{(m_{a,1} \frac{l_{arm,1}}{2} + m_{r,1} l_{rot,1})(c_{\alpha_1} - s_{\alpha_2} - c_{\alpha_3} + s_{\alpha_4})}{m_b + 4 \times (m_{a,1} + m_{r,1})} \\ y_G = \frac{(m_{a,1} \frac{l_{arm,1}}{2} + m_{r,1} l_{rot,1})(s_{\alpha_1} + c_{\alpha_2} - s_{\alpha_3} + c_{\alpha_4})}{m_b + 4 \times (m_{a,1} + m_{r,1})} \end{array}\right. \tag{2}$$

The global inertia matrix J also depends on the rotation angles α_i. We refer to reference [1] and find how to calculate it instantaneously:

$$J = \begin{bmatrix} I_{xx}(\alpha_i) & -I_{xy}(\alpha_i) & -I_{xz}(\alpha_i) \\ -I_{xy}(\alpha_i) & I_{yy}(\alpha_i) & -I_{yz}(\alpha_i) \\ -I_{xz}(\alpha_i) & -I_{yz}(\alpha_i) & I_{zz}(\alpha_i) \\ & & \end{bmatrix} \tag{3}$$

To describe the motion of the vehicle, we need two coordinate frames as shown in Figure 1 : The earth-fixed frame which denoted by $F_E(O_E, X_E, Y_E, Z_E)$ and the body-fixed frame which denoted by $F_B(O_B, X_B, Y_B, Z_B)$. The transformation between the two frames can be expressed using the following rotation matrix R:

$$R(\phi,\theta,\psi) = \begin{bmatrix} c_\psi c_\theta & c_\psi s_\theta s_\phi - c_\phi s_\psi & c_\psi s_\theta c_\phi + s_\phi s_\psi \\ s_\psi c_\theta & s_\psi s_\theta s_\phi + c_\phi c_\psi & s_\psi s_\theta c_\phi - s_\phi c_\psi \\ -s_\theta & s_\phi c_\theta & c_\theta c_\phi \end{bmatrix} \tag{4}$$

Where ϕ, θ and ψ are the roll, pitch and yaw angles along X_E,Y_E and Z_E axes.

$$\dot{\chi} = R(\phi,\theta,\psi)V^B \tag{5}$$

where $\dot{\chi} = (\dot{x}, \dot{y}, \dot{z})^T$ is the velocity vector of the vehicle in the earth frame F_E, $V^B = (u, v, w)^T$ is the velocity vector expressed in the body frame F_B.
The relation between angular velocities $\varpi = (p, q, r)^T$ of the quadrotor in the body frame and the angular velocities $\dot{\eta} = (\dot{\phi}, \dot{\theta}, \dot{\psi})^T$ in the earth frame is given as:

$$\dot{\eta} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \sin\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta \end{bmatrix} \varpi \tag{6}$$

The dynamic model of the reconfigurable quadrotor is written as follows:

$$\begin{cases} I_{xx}(\alpha_i)\dot{p} = (I_{yy}(\alpha_i) - I_{zz}(\alpha_i))qr + J_r\overline{\Omega}q - K_{fax}p^2 + u_2 \\ I_{yy}(\alpha_i)\dot{q} = (I_{zz}(\alpha_i) - I_{xx}(\alpha_i))pr - J_r\overline{\Omega}p - K_{fay}q^2 + u_3 \\ I_{zz}(\alpha_i)\dot{r} = (I_{xx}(\alpha_i) - I_{yy}(\alpha_i))pq - K_{faz}r^2 + u_4 \\ m\ddot{x} = -K_{ftx}\dot{x} + (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)u_1 \\ m\ddot{y} = -K_{fty}\dot{y} + (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)u_1 \\ m\ddot{z} = -K_{ftz}\dot{z} - g + (\cos\phi\cos\theta)u_1 \end{cases} \tag{7}$$

Where, m is the total mass of the vehicle, b is the lift coefficient, $\overline{\Omega} = \sum_{i=1}^{4} (-1)^{i+1}\Omega_i$ and Ω_i is the i^{th} rotor speed, K_{ftx}, K_{fty} and K_{ftz} are the transnational drag coefficients, K_{fax}, K_{fay} and K_{faz} are the aerodynamic friction coefficients, J_r is the rotor inertia.
The four control inputs of the quadrotor are the total thrust,the roll moment, the pitch moment and yaw moment:
$u = (u_1, u_2, u_3, u_4)^T$, with $u_1 = F$, $u_2 = \tau_\phi$, $u_3 = \tau_\theta$, $u_4 = \tau_\psi$.
$u = M \times \Omega_i^2$, where M is the control allocation matrix, which is given as:

$$M = \begin{bmatrix} b & b(y_{r,1} - y_G) & b(x_G - x_{r,1}) & d \\ b & b(y_{r,2} - y_G) & b(x_G - x_{r,2}) & -d \\ b & b(y_{r,3} - y_G) & b(x_G - x_{r,3}) & d \\ b & b(y_{r,4} - y_G) & b(x_G - x_{r,4}) & -d \end{bmatrix}^T \tag{8}$$

To test the efficiency of the controller that can deal with disturbances and neglected dynamics, it is usually preferable to take the simplified version of the complete dynamic model. So,we simplify the dynamic model (7) by neglecting some effects that have a minor impact in conditions of flying such as the drag forces, the gyroscopic moments and the aerodynamic friction torques. By assuming that the angles are small,we approximate the Euler angular velocities by the vehicle angular velocities: $\dot{\phi} \approx p, \dot{\theta} \approx q, \dot{\psi} \approx r$, the model (7) can be simplified as:

$$\begin{cases} I_{xx}(\alpha_i)\ddot{\phi} = (I_{yy}(\alpha_i) - I_{zz}(\alpha_i))\dot{\theta}\dot{\psi} + u_2 \\ I_{yy}(\alpha_i)\ddot{\theta} = (I_{zz}(\alpha_i) - I_{xx}(\alpha_i))\dot{\phi}\dot{\psi} + u_3 \\ I_{zz}(\alpha_i)\ddot{\psi} = (I_{xx}(\alpha_i) - I_{yy}(\alpha_i))\dot{\phi}\dot{\theta} + u_4 \\ m\ddot{x} = (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)u_1 \\ m\ddot{y} = (\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)u_1 \\ m\ddot{z} = -g + (\cos\phi\cos\theta)u_1 \end{cases} \tag{9}$$

From model (9), the two virtual controls are:

$$\begin{cases} u_x = \cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi \\ u_y = \cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi \end{cases} \tag{10}$$

We compute then the desired roll and pitch angles from equation (10):

$$\begin{cases} \phi_d = \arcsin(u_x\sin(\psi_d) - u_y\cos(\psi_d)) \\ \theta_d = \arcsin(\frac{u_x\cos(\psi_d) + u_y\sin(\psi_d)}{\cos(\phi_d)}) \end{cases} \tag{11}$$

The rotor is a DC motor actuating a propeller and governed by the following dynamics:

$$\begin{cases} V = RI + L\frac{dI}{dt} + K_e\Omega \\ T_m = J_r\frac{d\Omega}{dt} + C_s + T_r \end{cases} \tag{12}$$

where V is the voltage input, I is the current, R is the motor resistance, L is the motor inductance, $T_m = K_mI$ is the motor torque, $T_r = K_r\Omega^2$ is the motor load, K_e and K_m represent the electrical and the mechanical torque constant respectively. K_r is the load constant torque. J_r is the rotor inertia and C_s denotes the solid friction constant.
For small value of the inductance $(L \to 0)$, we get the following dynamic of the rotor:

$$V = \frac{\dot{\Omega} + \beta_2\Omega^2 + \beta_1\Omega + \beta_0}{b_m} \tag{13}$$

where $b_m = \frac{K_m}{RJ_r}$, $\beta_0 = \frac{-C_s}{J_r}$, $\beta_1 = \frac{-K_e K_m}{RJ_r}$, $\beta_2 = \frac{-K_r}{J_r}$ are constants.

The servomotor used in our vehicle is likened to a system which has a three-order transfer function closed loop [12]. This transfer function is given by:

$$F(s) = \frac{\alpha_i}{\alpha_{id}} = \frac{A(K_D s^2 + K_P s + K_I)}{Bs^3 + Cs^2 + Ds + E} \quad (14)$$

where α_{di} and α_i represent the input and the output of the system respectively, A, B, C, D are constants specific to the motor, K_P, K_I, K_D are the parameters of the PID controller.

3 INTEGRAL SLIDING MODE CONTROLLER DESIGN

Because of the complexity of reconfigurable quadrotors, we need a powerful control to overcome their change of configurations. The SMC approach is an excellent candidate for controlling these systems, thanks to its strong robustness. Therefore, in this section, an ISMC controller is designed to control our vehicle.
The state space representation of the reconfigurable quadrotor is given as follows:
Let $X = \left[\phi, \dot{\phi}, \theta, \dot{\theta}, \psi, \dot{\psi}, x, \dot{x}, y, \dot{y}, z, \dot{z}\right]^T$
$= [x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10}, x_{11}, x_{12}]^T \in R^{12}$
$u = (u_1, u_2, u_3, u_4)^T \in R^4$ and
$y = (x_1, x_3, x_5, x_7, x_9, x_{11})^T \in R^6$ be the state, the control input and the output respectively.
Where x, y, z are the positions, ϕ, θ, ψ are the attitudes of the quadrotor and $\dot{x}, \dot{y}, \dot{z}, \dot{\phi}, \dot{\theta}, \dot{\psi}$ are their change rates respectively.
Using the state space method, the dynamic model given in equation (10) can be written as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = a_1 x_4 x_6 + b_1 u_2 \\ \dot{x}_3 = x_4 \\ \dot{x}_4 = a_4 x_2 x_6 + b_2 u_3 \\ \dot{x}_5 = x_6 \\ \dot{x}_6 = a_7 x_2 x_4 + b_3 u_4 \\ \dot{x}_7 = x_8 \\ \dot{x}_8 = \dfrac{1}{m} u_x u_1 \\ \dot{x}_9 = x_{10} \\ \dot{x}_{10} = \dfrac{1}{m} u_y u_1 \\ \dot{x}_{11} = x_{12} \\ \dot{x}_{12} = -g + \dfrac{\cos x_1 \cos x_3}{m} u_1 \end{cases} \quad (15)$$

where

$$\begin{cases} a_1 = \frac{(I_{yy}(\alpha_i) - I_{yy}(\alpha_i))}{I_{xx}(\alpha_i)}, b_1 = \frac{1}{I_{xx}(\alpha_i)}, \\ a_2 = \frac{(I_{zz}(\alpha_i) - I_{xx}(\alpha_i))}{I_{yy}(\alpha_i)}, b_2 = \frac{1}{I_{yy}(\alpha_i)}, \\ a_3 = \frac{(I_{xx}(\alpha_i) - I_{yy}(\alpha_i))}{I_{zz}(\alpha_i)}, b_3 = \frac{1}{I_{zz}(\alpha_i)}. \end{cases} \quad (16)$$

In order to follow a desired reference trajectory, we define $e = X_d - X$ as the tracking error for both positions and attitudes.
Usually, the SMC controller contains an equivalent term u_{eq} that occurs on the sliding surface $S = 0$ and a discontinuous term u_{dis}, which drives the states of the system toward the sliding surface. $u = u_{eq} + u_{dis}$.
In this paper, we consider only actuator type of faults. For PFTC, the faults need to be considered during the process of the controller design, so an augmented sliding surface technique is introduced to further enhance the robustness of the regular SMC. For such a purpose, we add an integral term in the dynamics of the sliding surface [10].
Taking the roll dynamics, we choose the roll sliding surface as follows:

$$S_\phi = \dot{e_\phi} + \lambda_\phi e_\phi + k_{p\phi} \int e_\phi \quad (17)$$

where $\lambda_\phi > 0$ and $k_{p\phi} > 0$.

Let $V(S_\phi) = \frac{1}{2} S_\phi^2$ be the chosen Lyapunov function.

If $\dot{V}(S_\phi) < 0$, then $S_\phi \dot{S_\phi} < 0$, we can say that the Lyapunov stability is guaranteed.
Consider the derivative of the sliding surface defined as follows:

$$\dot{S_\phi} = -K_\phi sign(S_\phi) \quad (18)$$

where $K_\phi > 0$ is the switching gain.
from equation (17):

$$\begin{aligned} \dot{S_\phi} &= \ddot{e_\phi} + \lambda_\phi \dot{e_\phi} + k_{p\phi} e_\phi \\ &= \ddot{\phi}_d - \ddot{\phi} + \lambda_\phi \dot{e_\phi} + k_{p\phi} e_\phi \\ &= \ddot{\phi}_d - f_\phi - b_1 U_\phi + \lambda_\phi \dot{e_\phi} + k_{p\phi} e_\phi \end{aligned} \quad (19)$$

From equation (18) and equation(19), we get:

$$U_\phi = \frac{1}{b_1}(\ddot{\phi}_d - f_\phi + \lambda_\phi \dot{e_\phi} + k_{p\phi} e_\phi + K_\phi sign(S_\phi)) \quad (20)$$

where:

$$\begin{cases} U_{\phi eq} = \frac{1}{b_1}(\ddot{\phi}_d - f_\phi + \lambda_\phi \dot{e_\phi} + k_{p\phi} e_\phi) \\ \quad U_{\phi dis} = \frac{K_\phi}{b_1} sign(S_\phi) \end{cases} \quad (21)$$

Table 1 The reconfigurable quadrotor parameters.

b	$9.8.10^{-6}N.rad^{-1}.s^{-1}$	m	$1.1Kg$
d	$1.6.10^{-7}N.m.rad^{-1}.s^{-1}$	g	$9.81ms^{-2}$
a	$13cm$	l_{arm}, l_{rot}	$22cm, 21.6cm$

Similary, we find:

$$\begin{cases} U_\theta = \frac{1}{b_2}(\ddot{\theta}_d - f_\theta + \lambda_\theta \dot{e_\theta} + k_{p\theta}e_\theta + K_\theta sign(S_\theta)) \\ U_\psi = \frac{1}{b_3}(\ddot{\psi}_d - f_\psi + \lambda_\psi \dot{e_\psi} + k_{p\psi}e_\psi + K_\psi sign(S_\psi)) \\ U_x = \frac{m}{U_z}(\ddot{x}_d - f_x + \lambda_x \dot{e_x} + k_{px}e_x + K_x sign(S_x)) \\ U_y = \frac{m}{U_z}(\ddot{y}_d - f_y + \lambda_y \dot{e_y} + k_{py}e_y + K_y sign(S_y)) \\ U_z = \frac{m}{C_{x1}C_{x3}}(\ddot{z}_d - f_z + \lambda_z \dot{e_z} + k_{pz}e_z + K_z sign(S_z)) \end{cases} \tag{22}$$

The use of the discontinuous function $sign$ in the control law will excite the chattering phenomenon. To reduce it, a saturation function is needed.

$$sat(S) = \begin{cases} -\delta, if \quad S \leq -\delta \\ S, \ if -\delta < S < \delta \\ \delta, \ if \quad S \geq \delta \end{cases} \tag{23}$$

where δ is the boundary of the saturation function that is set small enough.

4 SIMULATION RESULTS AND DISCUSSION

In this section, we investigate the efficiency of the ISMC controller applied to the reconfigurable quadrotor where its parameters are depicted in Table 1.
The structure of the control loop is shown in Figure 3. The two positions x and y are controlled though two virtual control inputs (10) to reach the desired positions x_d and y_d, the altitude z is controlled by u_1 to reach the desired altitude z_d. The roll and pitch angles ϕ and θ are controlled by u_2 and u_3 to reach the desired roll and pitch angles ϕ_d and θ_d (11) calculated from the two virtual inputs. The yaw angles ψ is controlled by u_4 to reach the desired yaw angles ψ_d. Each SISO system is an ISMC controller developed in the previous section. The rotation angles α_i of the four arms are controlled using equation (14) to reach the desired angles by selecting the configuration of the quadrotor in the configuration switching block. Then we calculate instantaneously the global inertia matrix, the center of gravity and we update the allocation matrix (8) and the different ISMC controllers. The vehicle is expected to follow the circular trajectory defined by the following equations during 150 s :

$$x_d = 4\cos(\frac{\pi}{60}t) - 1, y_d = 4\sin(\frac{\pi}{60}t), z_d = 4, \psi_d = 0. \tag{24}$$

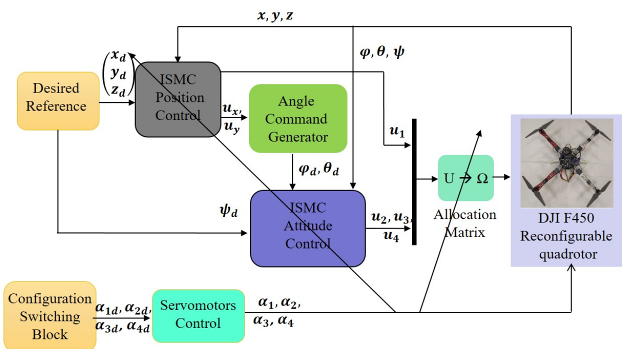

Fig. 3 Control structure.

The Matlab simulations have been carried out under these three scenarios to evaluate the effectiveness of the ISMC control strategy:
Scenario 1- ISMC applied to the system in fault-free situation.
Scenario 2- ISMC applied to the vehicle the vehicle which changes its configuration as follows : X-configuration from 0s to 40s, T-configuration from 40s to 80s, Y-configuration from 80s to 120s, O-configuration from 120s to 150s.
Scenario 3- ISMC applied to the system in faulty situation : loss of effectiveness in the first propeller (5%, 10%, and 25%). The fault is assumed to occur at 60s, it is introduced by multiplying the voltage input of the first rotor by a gain (1: no fault, 0: total loss of actuator, $0 < gain < 1$: loss of effectiveness).
We plot in Figures 4 and 5 the positions and attitude tracking in the two first scenarios. In Figure 6 (scenario 3), we plot the altitude tracking and the errors for different level of fault (0%, 5%, 10% and 25%) using regular SMC and Integral SMC. From the Figures 4 and 5 (scenario 1 and 2), we can see clearly that the reconfigurable quadrotor follows its reference trajectory in a good manner and satisfactory accuracy even the reconfigurable quadrotor changes the configuration. Figure 6 shows the effectiveness of the ISMC controller in presence of actuator fault compared to the regular SMC controller where we lose the control after the injection of 25% of fault. so, the integral term in the sliding surface enhances the robustness of the controller and compensates for the fault.

5 Conclusion

In this paper, an Integral Sliding Mode Controller based Passive Fault Tolerant Control is applied to a reconfigurable quadrotor with foldable arms. This controller approach is used to compensate for the partial loss of

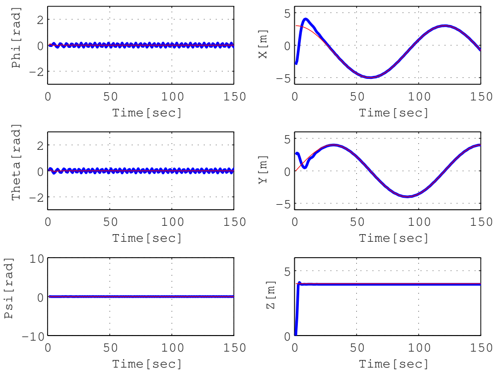

Fig. 4 Scenario 1: Positions and attitude tracking.

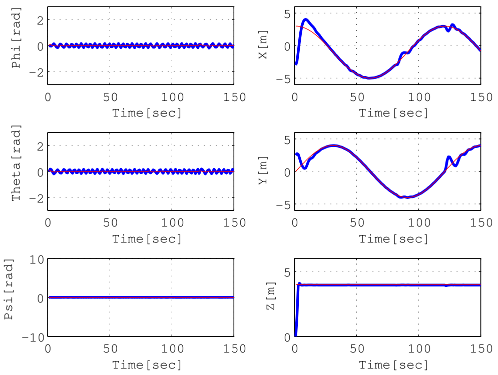

Fig. 5 Scenario 2: Positions and attitude tracking.

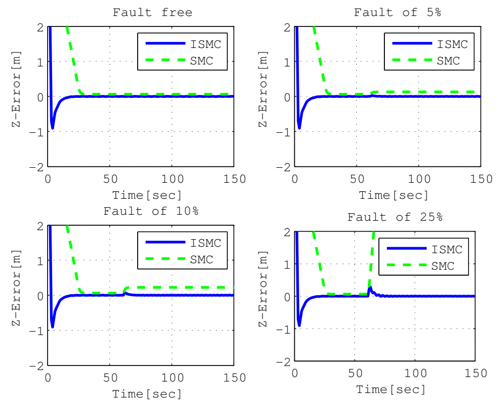

Fig. 6 Scenario 3: Altitude tracking errors.

effectiveness in one of its actuators and to raise the performance of the control even in commutation between different configurations. Satisfactory results were obtained in numerical simulations that will serve as a first step to pursue by Fault Detection and Diagnosis (FDD) system and the Active Fault Tolerant Control (AFTC) in the future.

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