Integral Sliding Mode and Second Order Sliding Mode Attitude and Altitude Tracking of a Quadrotor System

Theory and Experiment

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Abstract: In this paper Attitude and Altitude tracking control design of the four rotors helicopter will be considered. Two robust control algorithms will be designed for the case of stabilization and tacking of attitude and altitude system's outputs. The attitude controller is realized using an inertial measurement unit (IMU) based on MEMS sensors. The altitude control algorithm uses a sonar sensor output. The control algorithms designed are implemented on an embedded control system based on a dsPIC μC. The obtained experimental results demonstrate high performance of both controllers and robustness against disturbances.

1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have been designed in the military field since more than one half century. The main objective was to replace human pilot in a painful tasks and when the environment became hostile where the security of pilots is not assured such as: intervention in hostile environment, management of the natural risks, exploration of high buildings or contaminated tunnels, surveillance, rescue missions, movie filming, which were not possible before.

Nowadays, researches in this field know a very big progress with the advance development of electronic and digital systems. This progress has given birth to low cost very small and accurate electronic components, a powerful calculators, and sensors. All these, aimed to product a small embedded, autonomous and intelligent systems, able to perform missions with more effectiveness and reliability.

Miniature Vertical Takeoff and landing (VTOL) unmanned aerial vehicles (UAV's) offer challenging benchmark control problems and have been the focus for many researchers in the past few years (Brisset, 2004), (Bouabdallah, 2007). The VTOL UAV four rotor helicopter named X4, OS4, or known commonly as a quadrotor shown in Figure 1, is a mini-aircraft with four propellers.

Many researches addressed the modeling, the control, and the design of the quadrotor system (Bouabdallah, 2007), (Bouabdallah et al., 2004), (Escareño et al., 2006), (Osmani et al., 2010), (Hoffmann et al., 2007), (Kroo and Prinz, 2000), (Derafa, 2006), (Hanford, 2005), (Hamel et al., 2002), (McGilvray, 2004), (Bouadi et al., 2007), (Bouchoucha et al., 2008).

Generally speaking, improving the performance requires a good knowledge of the model as it is the case with the almost previous aforementioned works. Nevertheless it is still possible to achieve robustness and a highly efficient dynamics using a control techniques that does not need a good knowledge of the model; this is the case especially where some dynamics are neglected, the system parameters are variable or not known exactly (inertia, thrust and drag coefficients), or the system is subject to a disturbance like the wind guest. To overcome to that, robust control techniques have been proposed (Bouchoucha et al., 2008), (Waslander et al., 2006), (Bouabdallah et al., 2005), (Bouchoucha et al., 2011), (Seghour et al. 2011)..etc. Almost the designed techniques use sliding mode control technique and/or they implement only the attitude dynamics.

In this work, two control techniques are designed

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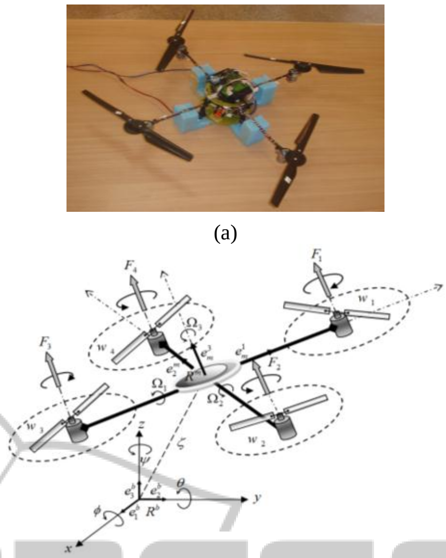
for the stabilization and the tracking of the attitude and the altitude of the quadrotor system; the integral sliding mode (ISM) and the second order sliding mode (SOSM). The benefit is to demonstrate the ability of both techniques to stabilize the system and the ability of the second order technique to eliminate the chattering phenomena while preserving the performance comparing with the classical sliding mode. The algorithms of both techniques are implemented in real time on a developed embedded control system based on a dsPIC µC to a quadrotor platform (a modified version of the Draganflyer of RCTOYS (Figure1)).

The rest of the paper is organized as follows: in section 2, a mathematic model of the quadrotor is presented. Section 3 is devoted to the design of both control approaches for the attitude and the altitude system's outputs. Real time implementation results of both control algorithms are presented in section 4. Finally, conclusions are made in section 5.



(a)

(b)

Figure 1: (a) Quadrotor helicopter of the LCC laboratory (EMP), (b) Quadrotor configuration and principles.

2 DEFINITION AND DYNAMICAL MODEL

A Quadrotor is an aircraft that is propelled by four rotors. This model of rotary wing vehicles is very interesting since the characteristic of taking-off and landing so the space of their maneuvers is very limited while comparing with fixed- wing aircraft.

The motion of this vehicle is controlled by varying the rotating speed of the four rotors to change the thrust and torques produced by each one. The front and rear motors rotate counter clockwise, while the two other motors rotate clockwise in order to counter the yaw torque produced at the movement of the aircraft (McGilvray, 2004), (Tayebi and McGilvray, 2004). The main thrust derives from the sum of thrusts of each rotor; it creates the vertical motion of the platform. The pitch and roll torques are derived respectively from the differences $(F_1 - F_3)$ and $(F_2 - F_4)$, while F_i is the thrust force of the rotor "i". The roll and pitch inclination create the translational motion along X and Y axis respectively.

The yaw torque is the sum of the reaction torques of each rotor produced by the shaft acceleration and the blade's drag $M_1 - M_2 + M_3 - M_4$ with $M_i = k_d \omega_i^2$, k_d is the drag coefficient and ω_i is the propeller speed of the motor i (Osmani et al., 2010), (Hanford, 2005).

The force F_i produced by the rotor "i" is proportional to the square of the propeller speed, $F_i = b\omega_i^2$ with b the proportionality constant of the thrust force.

The dynamics of the quadrotor is described in the space by six degrees of freedom according to the fixed inertial frame related to the ground.

To derive the dynamic model of the quadrotor, the Newton Euler formalism will be used on both translation and rotation motions; therefore to obtain the following equations (Hamel et al., 2002), (Bouabdallah et al., 2004), (McGilvray, 2004), (Derafa, 2006).

$$\begin{cases} \dot{\xi} = v \\ F_f + F_{dt} + F_g = m\ddot{\xi} \\ \tau_f - \tau_a - \tau_g = J\dot{\Omega} + \Omega \wedge J\Omega \end{cases} \tag{1}$$

In this work we mainly focus our interest to the attitude and the altitude dynamics and we consider the state space model of reduced dynamical model to simplify the control design as follows (Bouabdallah et al., 2004), (Derafa, 2006), (Boudane and Kamel, 2011):

$$\begin{aligned} X &= [x_1\ x_2\ x_3\ x_4\ x_5\ x_6\ \ x_7\ x_8]^T \\ &= [\varphi\ \ \theta\ \ \psi\ \ \dot{\varphi}\ \ \dot{\theta}\ \ \dot{\psi}\ \ z\ \ \dot{z}]^T \\ \dot{x}_1 &= x_2 \\ \dot{x}_2 &= a_1 x_4 x_6 + a_2 x_2^2 + a_3 \bar{\Omega} x_4 + b_1 U_1 \\ \dot{x}_3 &= x_4 \\ \dot{x}_4 &= a_4 x_2 x_6 + a_5 x_4^2 + a_6 \bar{\Omega} x_2 + b_2 U_2 \\ \dot{x}_5 &= x_6 \\ \dot{x}_6 &= a_7 x_2 x_4 + a_8 x_6^2 + b_3 U_3 \\ \dot{x}_7 &= x_8 \\ \dot{x}_8 &= a_9 x_8 + \frac{C_{x_1} C_{x_3}}{m} U_1 - g \end{aligned} \tag{2}$$

Where $\bar{\Omega} = \omega_1 - \omega_2 + \omega_3 - \omega_4$.
And the control inputs:

$$\begin{bmatrix} U_1 \\ U_2 \\ U_3 \\ U_4 \end{bmatrix} = \begin{bmatrix} k_p & -k_p & k_p & -k_p \\ -k_p & 0 & k_p & 0 \\ 0 & -k_p & 0 & k_p \\ k_d & k_d & k_d & k_d \end{bmatrix} \begin{bmatrix} \omega_1^2 \\ \omega_2^2 \\ \omega_3^2 \\ \omega_4^2 \end{bmatrix} \quad (3)$$

x_1, x_3, x_5, x_7 and x_2, x_4, x_6, x_8 are the roll, the pitch, the yaw, the altitude and their variations respectively.

The parameters $a_1, a_2 \ldots . a_8$ depend on the mass and the inertia of the system, the inertia of the rotors, the aerodynamic friction coefficients, the drag coefficients of translation.

The parameters b_1, b_2 depend on the inertia of the system and the distance between the center of the system and the center of the rotor; and the parameter b_3 depend on the inertia of the system.

m is the total mass of the quadrotor and g is the gravitational acceleration.

S and *C* represent the Sinus and Co-sinus functions respectively.

The rotors are driven by DC-motors with the well known equations (McGilvray, 2004), (Bouabdallah et al., 2004):

$$\begin{cases} L\dfrac{dI_a}{dt} = V_i - R_a I_a + k_m \omega_{mi}, \\ I_r \dot{\omega}_i = \tau_i - M_i. \end{cases} \quad (4)$$

Where R_a, I_a, k_m, L, ω_{mi} and τ_i are the motor resistance, armature current, motor constant, armature inductance, motor speed and the rotor torque respectively.

3 CONTROL LAWS DESIGN

This section is focused to the design of both control techniques proposed in this work i.e. the integral sliding mode and the second order sliding mode for the stabilization of the attitude and the altitude outputs of the quadrotor system.

Before presenting the design of both controls which is considered as an external loop we will present the control of each rotor i.e the propeller speed (internal loop).

The control torque developed by motor is a proportional controller with compensation of the drag torque resulting of the rotation of the propeller (McGilvray, 2004).

3.1 Control Design of the Quadrotor Dynamic

In order to stabilize the attitude and the altitude of the qaudrotor system, two robust control approaches will be designed: the integral sliding mode and the second order sliding mode. The benefit within the use of the integral term in the integral sliding mode is to improve the tracking errors.

To simplifier the demonstration of the design of both control approaches, the model of the qaudrotor presented in (2) can be rewritten as:

$$\begin{cases} \dot{x}_i = x_{i+1} \\ \dot{x}_{i+1} = f_i(x_i, x_{i+1}) + g_i U_j \end{cases} \quad i = 1,3,5,7\,;\, j = 2,3,4,1 \quad (5)$$

With $\begin{cases} f_1(.) = -a_1 x_4 x_6 - a_2 x_2^2 - a_3 \bar{\Omega} x_4 \\ f_3(.) = a_4 x_2 x_6 - a_5 x_4^2 + a_6 \bar{\Omega} x_2 \\ f_5(.) = -a_7 x_2 x_4 - a_8 x_6^2 \\ f_7(.) = a_{11} x_8 - g \end{cases}$ and $\begin{cases} g_1 = b_1 \\ g_3 = b_2 \\ g_5 = b_3 \\ g_7 = \frac{C_{x_1} C_{x_3}}{m} \end{cases}$

3.2 Integral Sliding-mode Control Approach

In this section we use Backstepping technique to design the integral sliding mode control. The benefit is the systematic choice of the Lyapunov function in the stability demonstration. The Backstepping control technique is designed for a system in triangular feedback form which is the case for the dynamic model of the quadrotor. In this technique the control design pass by several steps, in each step the actual state is controlled by the next state as a virtual control, until the last state which is controlled by the real control. The integral sliding mode (Skjetne and Fossen, 2004) is the well known sliding mode robust control (Utkin, 1978) augmented by an integral term to improve the tracking errors. However this approach suffers from the chattering phenomena that limit its realization.

The integral sliding mode will be designed for the stabilization of the attitude and the altitude of the qaudrotor model (5) in two steps.

The first step in this design is similar to the one for the Backstepping approach.

The most common way to include integral action in Backstepping is to use parameter adaptation. Another method is to augment the plant dynamics with the integral state $\dot{\xi}_i = x_{id} - x_i$ (Skjetne and Fossen, 2004). The resulting system is still in strict feedback form; however, the vector relative degree is increased to 3.

$$\begin{cases} \dot{\xi}_i = x_{id} - x_i \\ \dot{x}_i = x_{i+1} \\ \dot{x}_{i+1} = f_i(x_i, x_{i+1}) + g_i U_j \end{cases} \quad (6)$$

Step 1: in this step we consider the subsystem:

$$\begin{cases} \dot{\xi}_i = x_{id} - x_i \\ \dot{x}_i = x_{i+1} \end{cases}$$

And one define a new state z_i such as: $z_i = x_{id} - x_i$, and we introduce the first Lyapunov function candidate : $V_1(x) = \frac{1}{2}{z_i}^2 + \frac{1}{2}{\xi_i}^2$

Its time derivative is give by: $\dot{V}_1(x) = z_i(\xi_i - x_{i+1} + \dot{x}_{id})$

If we apply the Lyapunov theorem, i.e. by imposing $\dot{V}_1(x) \leq 0$ condition, the stabilization of z_i and ξ_i can be obtained by introducing a new virtual control input x_{i+1} where:

$$x_{i+1} = \dot{x}_{id} + \xi_i + \alpha_i z_i \text{ with } \alpha_i > 0$$

Step 2: Here we define the sliding surface S_i (Surface) [15]:

$$S_i = x_{i+1} - \dot{x}_{id} - \xi_i - \alpha_i z_i \quad (7)$$

And we consider the augmented Lyapunov function:

$$V_2(x) = \frac{1}{2}{z_i}^2 + \frac{1}{2}{S_i}^2 + \frac{1}{2}{\xi_i}^2 \quad (8)$$

The chosen law for the attractive surface is the time derivative of S_i satisfying ($S_i\dot{S}_i \leq 0$):

$$\dot{S}_i = -k_i sign(S_i) - k_{i+1}S_i \quad (9)$$

In the other hand we have:

$$\dot{S}_i = f_i(x_i, x_{i+1}) + g_i U_j - \ddot{x}_{id} - z_i - \alpha_i(-\xi_i - \alpha_1 z_i - S_i)$$
$$\dot{S}_i = f_i(x_i, x_{i+1}) + g_i U_j - \ddot{x}_{id} - z_i + \alpha_i(x_{i+1} - \dot{x}_{id})$$

As for the Backstepping approach, the control U_j is extracted as follow:

$$U_j = {g_i}^{-1}(-f_i(x_i, x_{i+1}) + \ddot{x}_{id} + z_i - \alpha_i(x_{i+1} - \dot{x}_{id}) \\ -k_i sign(S_i) - k_{i+1}S_i) \quad (10)$$

And the resulting control laws are given by:

$$\begin{aligned} U_1 &= (m/C_{x_1}C_{x_3})\{-a_9x_8 + g + z_7 - \alpha_7(x_8 - \dot{x}_{7d}) \\ &\quad -\mathrm{k_7sign(S_7) - k_8S_7}\} \\ U_2 &= {b_1}^{-1}\{(a_1x_4x_6 + a_2x_2^2 + a_3\bar{\Omega}x_4 + z_1 - \alpha_1(x_2 - \dot{x}_{2d}) \\ &\quad -\mathrm{k_1sign(S_1) - k_2S_1}\} \\ U_3 &= {b_2}^{-1}\{-a_4x_2x_6 + a_5x_4^2 - a_6\bar{\Omega}x_2 + z_3 - \alpha_2(x_4 - \dot{x}_{2d}) \\ &\quad -\mathrm{k_3sign(S_3) - k_4S_3}\} \\ U_4 &= {b_3}^{-1}\{a_7x_2x_4 + a_8x_6^2 + z_5 - \alpha_3(x_6 - \dot{x}_{6d}) \\ &\quad -\mathrm{k_5sign(S_5) - k_6S_5}\} \end{aligned} \quad (11)$$

In the implementation, the sign (signe) function is replaced by the Sat function in a boundary Layer (Slotine, 1985) to reduce the chattering problem.

3.3 Second Order Sliding Mode Control (Super-Twisting Algorithm)

The attitude and the altitude dynamic of the quadrotor in (2 model) or (5) have relative degree one with respect to the sliding surface defined in (12) (the control input appears in the first derivative of the sliding surface (14)). To remedy of the chattering phenomena in classical integral sliding mode, the second order sliding mode by using the super-twisting algorithm will be applied (Levant, 1997), (Emelyanov et al., 1986), (Emelyanov et al., 1996), (Fridman and Levant, 1996), (Nollet et al., 2008).

Let us define here a new sliding surface $s_{si}(x)$ of the system based on the model of the form (6) without the first equation:

$$s_{si}(x) = \dot{z}_i + \lambda_i z_i \text{ , with } i = 1,3,5,7 \quad (12)$$

Its time derivative is given by:

$$\dot{s}_{si}(x) = \ddot{z}_i + \lambda_i \dot{z}_i = \lambda_i(\dot{x}_{id} - x_{i+1}) + \ddot{x}_{id} - \dot{x}_{i+1} \quad (13)$$

Replacing $\dot{x}_{i+1}$ by its equation given in (5) or (6),$\dot{s}_{si}$ become:

$$\dot{s}_{si} = \lambda_i(\dot{x}_{id} - x_{i+1}) + \ddot{x}_{id} - f_i(x_i, x_{i+1}) - g_i U_j \quad (14)$$

Using the principle of second order sliding mode by the super-twisting algorithm (Bouchoucha et al., 2011), (Nollet et al., 2008) the control input U_j is given by:

$$U_j = -{g_i}^{-1}\left(f_i(x_i, x_{i+1}) - \ddot{x}_{id} - \lambda_i(x_{i+1} - \dot{x}_{id}) + w_{st,j}(s_{si})\right) \quad (15)$$

With $i = 1,3,5,7; j = 1,2,3,4$

With the super-twisting controls $w_{st,j}(s_{si})$ are given by:

$$w_{st,j}(s_{si}) = -\sigma_i |s_{si}|^{1/2} sign(s_{si}) + u_{1,j}(t) \quad (16)$$
$$\dot{u}_{1,j}(t) = -\beta_i sign(s_{si}) \quad (17)$$

Finally the control inputs U_1, U_2, U_3, U_4 are given by:

$$\begin{aligned} U_1 &== -(m/C_{x_1}C_{x_3})\left(-a_9x_8 + g - \lambda_7(x_8 - \dot{x}_{8d}) + w_{st,1}(s_{si})\right) \\ U_2 &= -{b_1}^{-1}\left(-a_1x_4x_6 - a_2x_2^2 - a_3\bar{\Omega}x_4 - \lambda_1(x_2 - \dot{x}_{2d}) + w_{st,2}(s_{si})\right) \\ U_3 &= -{b_2}^{-1}\left(a_4x_2x_6 - a_5x_4^2 + a_6\bar{\Omega}x_2 - \lambda_3(x_4 - \dot{x}_{4d}) + w_{st,3}(s_{si})\right) \\ U_4 &= -{b_3}^{-1}\left(-a_7x_2x_4 - a_8x_6^2 - \lambda_5(x_6 - \dot{x}_{6d}) + w_{st,4}(s_{si})\right) \end{aligned} \quad (18)$$

Choosing the values of σ_i and β_i sufficiently large, allow to the tracking errors z_i and $\dot{z}_i$ to tend to zero in finite time. The robustness to the parametric uncertainties can be ensured by increasing the gains σ_i and λ_i (Slotine, 1985).

4 REAL TIME IMPLEMENTATION

4.1 Experimental Setup

In order to validate the control laws developed in the previous section, we implemented the controllers on the embedded control unit based on a dsPIC µC. The attitude outputs are measured using the IMU 3DM-GX1 of microstrain and the altitude is measured by the ultrasonic sensor SRF08. The propellers speeds are measured using a Hall Effect sensor combined with little magnets mounted under the main rotor gear. The sampling period is 30ms for the attitude motion and 65ms for the altitude motion (the ultrasonic sensor give the output each 65ms). We are made for both control laws two experiment. In the first experiment the attitude motion is stabilized with a fixed trust U1=2.6N and the system is mounted on fixed base knee-joint. In the second experiment where we will give it a great interest we have liberated the system to stabilize its altitude with attitude is stabilized around an equilibrium point zero. The controller's parameters for both controllers were tuned by trial and error, until obtaining a better responses performance of the system.

4.2 Attitude Motion

For both control law and for the case of stabilization around the equilibrium point and for more convenience the initial values for the roll, pitch, and yaw angles are taken almost the same for both controllers.

The results obtained for both controllers are shown in the figure.2

The following graphs show the obtained performances:

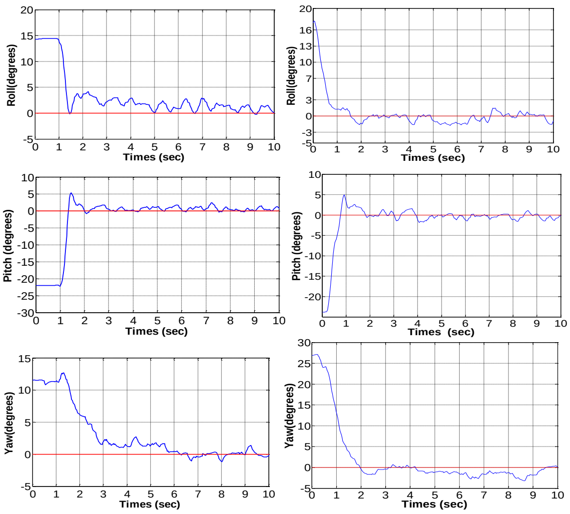


Figure 2: Attitude stabilization :(left) integral sliding mode (**ISM**), (right) second order sliding mode (**SOSM**).

The results obtained demonstrate the stabilization of all the system outputs for both controllers.

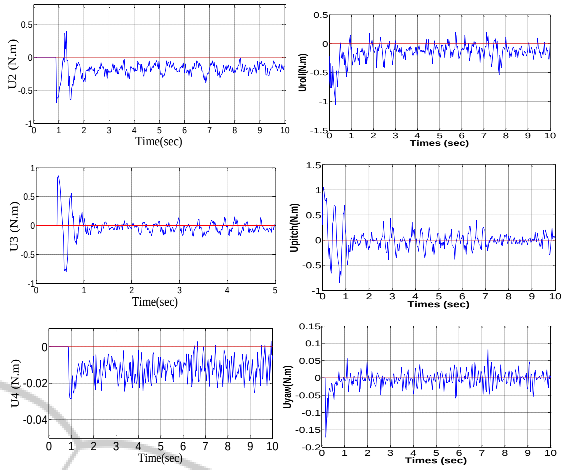


Figure 3: Control inputs: (left) ISM, (right) **SOSM.**

However the second order sliding mode demonstrates more superiority in term of performance (settling time and accuracy).

To test the robustness of both approaches two experiments have been performed.

In the first experiment the robustness test have been realized to deal with the external load disturbance and for more convenience, we have maintained the same work conditions; a mass of 50 g is fixed on the end of the system axis. The test is made for the roll and the pitch axis and because the symmetrical nature of the system we will present only the results of the roll axis.

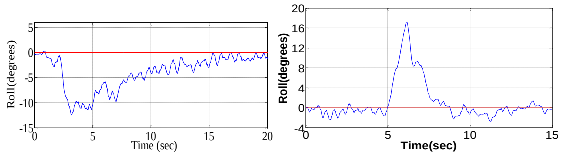


Figure 4: Roll response with disturbance: (Left) ISM, (Right) SOSM.

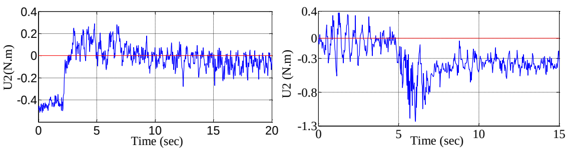


Figure 5: Control inputs with disturbance: (Left) ISM, (Right) SOSM.

The results obtained (Fig.4) show the ability of both controllers to handle the effects of disturbance. However, the integral sliding mode take more time (13 seconds) to reject the disturbance effect than the second order sliding mode (4 seconds) which confirm the invariance property of SOSM to eliminate the chattering while keeping the system performance comparing with integral sliding mode with a boundary layer even with an integral term.

The second experiment, both controllers are tested to a desired trajectories tracking. For that a hybrid cycloid and sinusoidal reference are used.

The results obtained (Fig.6) show that both controllers ensure the trajectories tracking. However, the SOSM controller demonstrates better behavior in term of accuracy, settling time and overshoot comparing with the ISM controller.

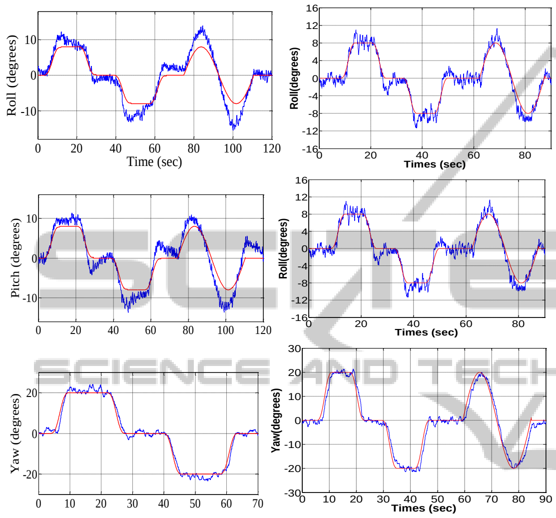


Figure 6: Desired Angles (Red) and real Angles outputs (Blue): (left) **ISM**, (right) **SOSM.**

4.3 Altitude Motion

The altitude of the quadrotor will be considered here for the case of stabilization and robustness to external disturbances and desired trajectory tracking.

For the stabilization case, the system is controlled to stabilize the altitude around 40cm as a set point. The results obtained for both controllers are shown in the figure 7, 8 and 9.

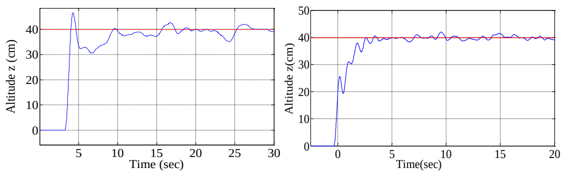


Figure 7: Altitude stabilization: (left) **ISM**, (right) **SOSM.**

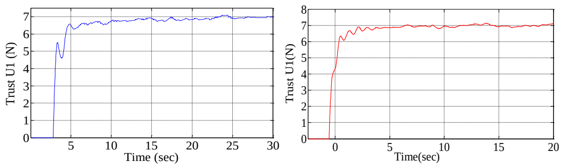


Figure 8: Altitude control input (Trust U1): (left) **ISM**, (right) **SOSM.**

The results obtained (fig.7, fig.8, fig.9) show the stabilization of the altitude of the two controllers with a superiority of the SOSM controller in relation to the ISM controller in term of accuracy, settling time and overshoot.

To verify the robustness of the proposed approaches for the altitude output; external disturbance rejection and trajectory tracking tests are realized.

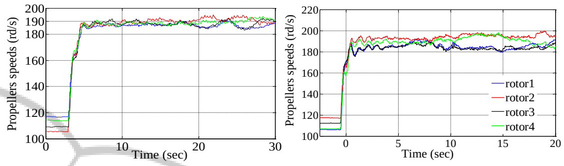


Figure 9: Propellers speeds (Trust U1): (left) **ISM**, (right) **SOSM.**

The external disturbance realized by adding a 15% of the value of the actual control input U1 to its next value.

The results obtained (fig.10 and fig.11) show that even the deviation of the altitude output from its stable value in the instance of the application of the disturbance; both controllers damp the effect of the disturbance in finite time. However and like it seems clearly the SOSM controller is largely better in term of the time (4sec) take it to handle the effect of the disturbance than the ISM (15 sec) controller.

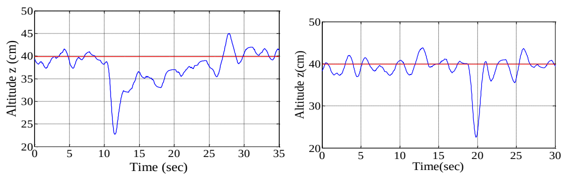


Figure 10: Altitude response with disturbance: (Left) **ISM**, (Right) **SOSM**.

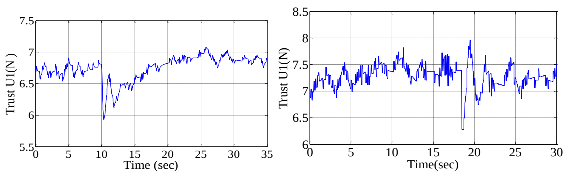


Figure 11: Altitude control input (Trust U1) with disturbance: (Left) **ISM**, (Right) **SOSM.**

In the second robustness test, the system is submitted to a cycloidal reference trajectory. The altitude outputs and the corresponding control inputs U1 of the quadrotor for the both controllers are given in the figure 12 and 13 respectively.

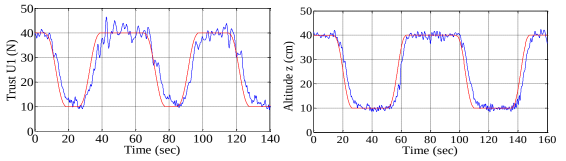


Figure 12: Desired Altitude (Red) and real Altitude (Blue): (left) **ISM**, (right) **SOSM.**

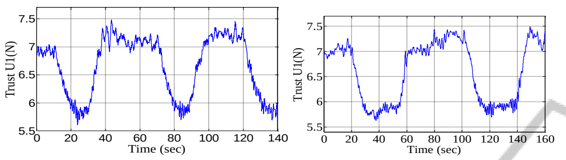


Figure 13: Control inputs: (left) **ISM**, (right) **SOSM**.

These results show that both approaches ensure the tracking of the cycloidal reference trajectory. However the SOSM approach shows better tracking performance than the ISM approach.

5 CONCLUSIONS

This paper presents the real time implementation of two robust controllers on a realized embedded control system for the stabilization and the tracking of the quadrotor system. The embedded control system is based on a dsPIC µC. A 3DM-GX1 IMU, SRF08 sonar and Hall Effect sensors with a little magnet are used to measure the attitude, the altitude and the propellers speeds of the quadrotor respectively. The robust approaches used are the integral sliding mode with a boundary layer method and the second order sliding mode. The experimental results obtained demonstrate the superiority of the SOSM controller comparing with ISM controller in term of performance (accuracy, settling time and overshoot) for the case of stabilization and tracking and robustness to external disturbances while cancelling the chattering phenomena. These results validate theoretical results and confirm that the SOSM keep the invariance property in term of performance while reducing the effect of the chattering which is not the case of the sliding mode (with a boundary layer method) even with additional integral term.

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