

Adjustment mechanism with sliding mode for adaptive PD controller applied to unmanned fixed-wing MAV altitude

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ABSTRACT

This work presents an adjustment mechanism with the sliding modes technique to design a proportional derivative (PD) controller with adaptive gains. The objective and contribution are to design a robust adjustment mechanism in the presence of unknown and not modeled perturbations in the system; this perturbation can be considered wind gusts. The robust adjustment mechanism is designed with the MIT rule and the gradient method with the sliding mode theory. The adaptive PD obtained is applied to regulate unmanned fixed-wing miniature aerial vehicle (MAV's) altitude.

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1. INTRODUCTION

The development and use of unmanned aerial systems (UAVs) have been increasing in the last decade [1], [2], and the theory about adaptive control is fundamental in the development and advances in this field. And even the applications of the fixed-wing UAVs are increasing; some applications are: forest fire detection, in civil engineering (topography, analysis structural and others) [3], photogrammetry, and military applications [4], car detection [5] or for landing [6]. We can find some works in the scientific literature refers to adaptive control based on the MIT rule. For example, in [7] is developed a model reference based on a proportional integral derivative (PID) controller. Compared with a conventional or ordinary reference model, this is done to get better performance in the control of the velocity of a DC motor. Pawar and Parvat [8] is presented a modification in the structure of an model reference adaptive control (MRAC) the modification is based on a PID controller as in [7]. Still, the difference is that in [8] the PID is used between other controllers based in MRAC and the plant, the proposed of [8] has the objective of improving the transient response of the plant, and it uses the known MRAC structure [9]. Whereas in [10] the direct model reference adaptive and an internal controller is applied to doubly fed induction generator and in this work, is proposed the adjustment mechanism based on MIT rule. Still, in addition, the Perrin equation has been added to this mechanism with an improved internal model controller filter design. Thus, in [10] the adjustment mechanism using the Perrin equation is intending to avoid the selection of the adaptive gain by a heuristic method.

Priyank and Nigam [11] is presented the design of a MRAC for a second-order system, that is, is presented a modified MIT rule to resolve two problems that present the MIT rule, these problems are that with a sufficiently large selection of the adaptation gain or in the magnitude of the reference signal the system tends to the instability. And then, to give a solution to these problems, in [11] a normalized algorithm with

MIT rule is presented to develop the control law. Riache *et al.* [12] is presented an adaptive robust controller applied to quadrotor with a serial robot manipulator onboard, the control objective in [12] is that during the flight, move the robot arm and keep the desired trajectory. On the other hand, the works [7], [8], [10], [11] presents simulations results using the Matlab software as well as in this work. We can find other adaptive controllers applied to fixed-wing unmanned aerial vehicle (UAV) as in [13] where is presented the guidance system makes the airplane follows pre-computed references using a novel iterative model predictive scheme, which can handle the nonlinear optimization problem by successive linearizations (starting the algorithm using a robust l_1 navigation law. On the other hand, in [14] is presented an adaptive control to compensate the unknown parameters of an unmanned aerial vehicle with fixed-wing in normal condition flight, the control objective is to achieve a desired speed and roll angle, and after that to track desired path with minimum error. An adaptive neuro-fuzzy controller is presented in [15], where is developed an autonomous flight controller for fixed-wing UAV based on adaptive neuro-fuzzy inference system (ANFIS). Three ANFIS modules are designed for controlling the altitude, the heading angle, and the speed of the UAV. In this way, the UAV position is controlled in three-dimensional space: altitude, longitude, and latitude position. The simulation results show the capability of the designed approach and its very satisfactory performance with good stability and robustness against UAV parametric uncertainties and external wind disturbance.

Zhou *et al.* [16] is presented an attitude dynamic model of unmanned aerial vehicles, considering a strong coupling in the aerodynamic model. Model uncertainties and external gust disturbances are considered during designing the attitude control system for UAVs and feedback linearization and MRAC are integrated to design the attitude control system for a fixed-wing UAV. Qiu *et al.* [17] is presented the dynamics and attitude control of a mass-actuated fixed-wing UAV (MFUAV) with an internal slider. Based on the derived mathematical model of the MFUAV, the influence of the slider parameters on the dynamical behavior is analyzed, and the ideal installation position of the slider is given. Besides, it is revealed that the mass-actuated scheme has a higher control efficiency for low-speed UAVs. To deal with the coupling, uncertainty, and disturbances in the dynamics, an adaptive sliding mode controller based on fuzzy system, radial basis function (RBF) neural network, and sliding mode control are proposed. Patel and Bhandari [18] is presented a neural network-based nonlinear adaptive controller for a fixed-wing UAV, in [18] is used both offline and online trained neural networks. Multi-layer perceptron (MLP) networks are used for the training of both the off-line and online networks.

Even in the scientific literature, we can find some controllers for fixed-wing UAVs that are not adaptive controllers, as in [19] is proposed a comprehensive approach combining backstepping with PID controllers for simultaneous longitudinal and lateral-directional control of fixed-wing UAVs. Kayacan *et al.* [20] is presented a learning control strategy is preferred for the control and guidance of a fixed-wing unmanned aerial vehicle to deal with lack of modeling and flight uncertainties. For learning the plant model and changing working conditions online, a fuzzy neural network (FNN) is used in parallel with a conventional proportional (P) controller. Among the learning algorithms in the literature, a derivative-free one, the sliding mode control (SMC) theory-based learning algorithm, is preferred as it has been proved to be computationally efficient in real-time applications. On the other hand, in [21] is presented a model-free control (MFC) that is an algorithm dedicated to systems with poor modeling knowledge. Indeed, the costs to derive a reliable and representative aerodynamic model for UAVs motivated the use of such a controller.

We can see that every application or control theory applied to fixed-wing UAVs is necessary to develop an altitude control law. Then, in this work, our control objective is to design an altitude controller in the presence of perturbations in unmanned fixed-wing miniature-aerial-vehicle (MAVs); the perturbations mentioned are the wind gusts. Exists altitude controllers with gains definite fix, but the problem with such controllers is that it works in specific altitudes (fix flight points). On the other side, adaptive controllers exist that can work in different altitude points but present some problems in keeping control objectives in perturbations. So in this work, we have proposed an adaptive controller that can lead an unmanned fixed-wing MAV to different altitudes in the presence of wind gusts (perturbations).

As is mentioned in [9] the problem to resolve an model reference adaptive system (MRAS) is to determine the adjustment mechanism to stabilize the system and which achieves the error to zero. Then a solution to this problem is the development of a proportional-derivative (PD) controller with adaptive gains. This adaptation is based on the adaptive scheme known as MRAS. Then, to achieve the control objective, we have designed a robust adjustment mechanism for the adaptive gains of a PD controller. Our proposal to design it is using the MIT rule, an approach to model-reference adaptive control and gradient method with sliding

mode theory. The obtained robust adaptive mechanism for the adaptive controller PD is going to compare with the known adaptive mechanism developed in [9], that is, to demonstrate the advantages in the error and the control effort concerning developed in this work.

The organization of the document is the following: in the section 2. is presented the longitudinal model which defines the fixed-wing MAV and in the section 3. is shown the design of the adaptive mechanism and the PD controller. In section 4. is presented the simulation results obtained, and finally, section 5. presents the conclusions and the future work.

2. LONGITUDINAL MODEL

To regulate the altitude of the fixed-wing MAV is used the aerodynamic model which defines the longitudinal model of an airplane. Then, this aerodynamic model has been obtained based on the second movement law of Newton; some considerations are taken for the model obtention, that is, the earth is considered as plane due to the fixed-wing MAV is going to fly short distances, and is not consider any flexible part in the airplane for the dynamic model. Then, the longitudinal model of the airplane has been defined as (1), (2), (3), (4) and (5).

$$\dot{V} = \frac{1}{m}(-D + T \cos \alpha - mg \sin \gamma) \quad (1)$$

$$\dot{\gamma} = \frac{1}{mV}(L + T \sin \alpha - mg) \sin \gamma \quad (2)$$

$$\dot{\theta} = q \quad (3)$$

$$\dot{q} = M_q q + M_{\delta_e} \delta_e \quad (4)$$

$$\dot{h} = V \sin(\theta) \quad (5)$$

Where V is the airplane speed, α describes the angle of attack, γ represents the flight-path angle, and θ denotes the pitch angle. In addition, q is the pitch angular rate (concerning the y -axis of the aircraft body), T denotes the force of engine thrust, h is the airplane altitude [22], [23] and δ_e represents the elevator deviation. The aerodynamic effects on the airplane are obtained by the lift force L and the drag force D . The total mass of the airplane is denoted by m , g is the gravitational constant, and I_{yy} describes the component y of the diagonal of the inertial matrix. The value of the angle of attack is obtained by using the following relation $\alpha = \theta - \gamma$ [22], the Figure1 shows the variables implies in the pure pitch motion to apply control in altitude. In aerodynamics, M_q and M_{δ_e} are the stability derivatives implicit in the pitch motion. The lift force L , the drag force D are defined as (6) and (7) [22], [23].

$$L = \bar{q} S C_L \quad (6)$$

$$D = \bar{q} S C_D \quad (7)$$

The aerodynamic stability derivatives are defined by: where \bar{q} denotes aerodynamic pressure. S represents the wing platform area, and \bar{c} is the mean aerodynamic chord. C_D and C_L are the aerodynamic coefficients for drag force and lift force, respectively.

$$M_q = \frac{\rho S V \bar{c}^2}{4 I_{yy}} C_{m_q}$$

$$M_{\delta_e} = \frac{\rho V^2 S \bar{c}}{2 I_{yy}} C_{m_{\delta_e}}$$

Where:

ρ : Air density (1.05 kg/m^3).

S : Wing area (0.09 m^2).

\bar{c} : Standard mean chord (0.14 m).

b : Wingspan, (0.914 m).

I_{yy} : Moment of inertia in pitch ($0.17 \text{ kg} \cdot \text{m}^2$).

C_{m_q} : Dimensionless coefficient for longitudinal movement, it is obtained experimentally (-50).

$C_{m_{\delta_e}}$: Dimensionless coefficient for elevator movement, it is obtained experimentally (0.25).

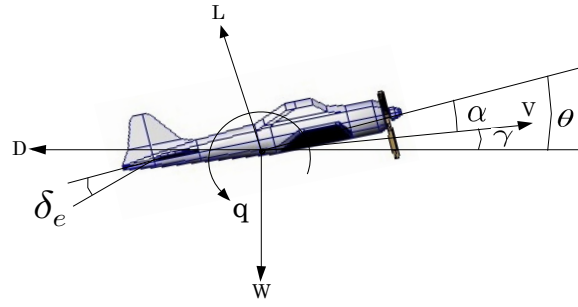


Figure 1. Pure pitching motion

3. CONTROLLER DESIGN

To design the adaptive controller for altitude, we have considered the (3), (4) and (5), this is due to which the (1) represents the velocity of the airplane. Still, for the simulations of this work, it is considered as constant, and the (2) is the flight path produced by the wind. In this work, we are designing the control law over the solid (aircraft body). For that reason, the control law is designed without considering the wind equations which define the airplane dynamics. Then, the altitude error is defined as $\tilde{e}_h = h_d - h$, where h_d is the desired altitude and h is the actual altitude.

The desired altitude is achieved by controlling the pitch angle. Thus we have defined an error for this angle, given by $\tilde{e}_\theta = \theta_d - \theta(t)$, where $\theta_d = \arctan(\tilde{e}_h/\zeta)$ is the desired pitch angle, and ζ denotes the longitude from the center of mass of the miniature aerial vehicle to the nose of it. Consider the equations (3) and (4), δ_e defines the control input. Thus, The adaptive control is given by (8).

$$\delta_e = \hat{k}_{pa}\tilde{e}_\theta + \hat{k}_{va}\dot{\tilde{e}}_\theta \quad (8)$$

Where \hat{k}_{pa} and \hat{k}_{va} are called as the position and velocity gains, respectively, these are the adaptive gains. The gains of the PD control have implicit a subscript to indicate the algorithm that has been applied as adjustment mechanism, a_1 corresponds to the MIT rule, a_2 corresponds to the MIT rule with sliding-mode, a_3 uses the MIT rule with 2-sliding-mode, and a_4 represents the MIT rule with HOSM. Therefore, for the design of the MIT rule, it is introduced an error given by (9).

$$e_{\theta_m} = \theta_m - \theta \quad (9)$$

Where θ_m is the output from the reference model, we have followed the methodology that has been presented in [9] for the MIT rule, taking this into account, the aerodynamic model has been transformed into the representation of a transference function to develop the derivatives of sensitivity; these have been obtained by computing partial derivatives concerning the controller parameters \hat{k}_{pa} and \hat{k}_{va} . Thus, the closed-loop transfer function with the adaptive PD controller has been defined as (10).

$$\theta = \frac{M_{\delta_e}(\hat{k}_p + \hat{k}_v s)}{s^2 + (M_q + M_{\delta_e}\hat{k}_v)s + M_{\delta_e}\hat{k}_p}\theta_d \quad (10)$$

And the model of reference for the altitude dynamics has been defined as (11).

$$\theta_m = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}\theta_d \quad (11)$$

Where $\zeta = 3.17$ and $\omega = 3.16$. Considering (9), (10) and (11) and calculating the partial derivatives with respect to \hat{k}_{pa} and \hat{k}_{va} , it is obtained as (12) and (13).

$$\frac{\partial e_{\theta_m}}{\partial \hat{k}_p} = \frac{M_{\delta_e}}{s^2 + (M_q + M_{\delta_e}\hat{k}_v)s + M_{\delta_e}\hat{k}_p}(\theta - \theta_d) \quad (12)$$

$$\frac{\partial e_{\theta_m}}{\partial \hat{k}_v} = \frac{M_{\delta_e} s}{s^2 + (M_q + M_{\delta_e}\hat{k}_v)s + M_{\delta_e}\hat{k}_p}(\theta - \theta_d) \quad (13)$$

Generally, the expressions (12) and (13) cannot be used due to the unknown parameters \hat{k}_{pa} and \hat{k}_{va} . So that, an optimum case has been assumed and it is defined as (14).

$$s^2 + (M_q + M_{\delta_e} \hat{k}_{vl})s + M_{\delta_e} \hat{k}_{pl} = s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (14)$$

thus, after these approximations, we have obtained the differential equations of the adaptive PD controller.

$$\dot{\hat{k}}_{pa1} = -\gamma_1 \left(\frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) e_{\theta_m} \quad (15)$$

$$\dot{\hat{k}}_{va1} = -\gamma_2 \left(\frac{s}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) e_{\theta_m} \quad (16)$$

Now, it is proposed an MIT rule with second-order sliding mode; this approach is different than the defined in [9]. Thus, it is defined a sliding-mode surface as $s_1 = \dot{\theta}_m - q + k_1 e_{\theta_m}$ (we are searching increase the stability of the adjustment mechanism), where k_1 is a positive gain. Then, the differential equations of the adaptive controller, with the methodology by sliding-mode, are given by (17) and (18).

$$\dot{\hat{k}}_{pa2} = -\gamma_1 \left(\frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) (\beta_p(s_1)) \quad (17)$$

$$\dot{\hat{k}}_{va2} = -\gamma_2 \left(\frac{s}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) (\beta_v(s_1)) \quad (18)$$

Where β_p and β_v are positive values. Due to the chattering effect of the first order sliding-mode, let us design an adjustment mechanism with a second-order sliding mode. This second-order sliding mode includes a robust differentiator of first-order [24]. This differentiator is defined by (19).

$$\begin{aligned} \dot{x}_0 = v_0 &= -\lambda_0 |x_0 - s_1|^{1/2} (x_0 - s_1) + x_1 \\ \dot{x}_1 &= -\lambda_1 (x_1 - v_0) \end{aligned} \quad (19)$$

Where x_0 and x_1 are real-time estimations of s_1 and \dot{s}_1 , respectively. The values of λ_1 and λ_2 are positives and constants. Thus, the differential equations of the adaptive PD controller with a second-order sliding mode are defined by (20) and (21).

$$\dot{\hat{k}}_{pa3} = -\gamma_1 \left(\frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) (\beta_p(s_1) + \beta_{p2}(\dot{s}_1)) \quad (20)$$

$$\dot{\hat{k}}_{va3} = -\gamma_2 \left(\frac{s}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) (\beta_v(s_1) + \beta_{v2l}(\dot{s}_1)) \quad (21)$$

Where β_p , β_{p2} , β_v and β_{v2l} are positive definite gains.

To reduce or eliminate the chattering effect in the second-order sliding mode, we have designed an adjustment mechanism with HOSM. To design the adjustment mechanism, it is necessary a robust differentiator of second-order [24], which is given by (22).

$$\begin{aligned} \dot{x}_0 = v_0 &= -\lambda_0 |x_0 - s_1|^{2/3} (x_0 - s_1) + x_1 \\ \dot{x}_1 = v_1 &= -\lambda_1 |x_1 - v_0|^{1/2} (x_1 - v_0) + x_2 \\ \dot{x}_2 &= -\lambda_2 |x_2 - v_1| \end{aligned} \quad (22)$$

Where x_0 , x_1 y x_2 are real-time estimations of s_1 , \dot{s}_1 and \ddot{s}_1 . The values of λ_0 , λ_1 and λ_2 are defined as positive constants. Finally, the differential equations of the adaptive PD controller with HOSM are defined by (23) and (24).

$$\begin{aligned} \dot{k}_{pa_4} &= -\gamma_1 \left(\frac{1}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) \\ &\quad (\alpha_{pl} [\ddot{s}_{1l} + 2(|\dot{s}_{1l}|^3 + |s_{1l}|^2)^{1/6} \\ &\quad (\dot{s}_{1l} + |s_{1l}|^{2/3}(s_{1l}))]) \end{aligned} \quad (23)$$

$$\begin{aligned} \dot{k}_{va_4} &= -\gamma_2 \left(\frac{s}{s^2 + 2\zeta\omega_n s + \omega_n^2} (\theta - \theta_d) \right) \\ &\quad (\alpha_v [\ddot{s}_1 + 2(|\dot{s}_1|^3 + |s_1|^2)^{1/6} \\ &\quad (\dot{s}_1 + |s_1|^{2/3}(s_1))]) \end{aligned} \quad (24)$$

Where α_p and α_v are positive and constant gains.

4. SIMULATION RESULTS

To describe the simulations results with the MIT-rule with sliding mode theory, we have analyzed the results with the \mathcal{L}_2 -norm [25], that is, to analyze the error signals and the control effort with the different adaptive mechanism proposed. Then, we have applied the \mathcal{L}_2 -norm to the error (25):

$$\mathcal{L}_2[e_h] = \sqrt{\frac{1}{T-t_0} \int_{t_0}^T \|e_h\|^2 dt} \quad (25)$$

The \mathcal{L}_2 -norm is also used to obtain the effort of the control law, and it is defined as (26):

$$\mathcal{L}_2[\delta_e] = \sqrt{\frac{1}{T-t_0} \int_{t_0}^T \|\delta_e\|^2 dt} \quad (26)$$

Thus, with the use of the (25) and (26) are obtained the errors and efforts, see the Table 1.

Table 1. \mathcal{L}_2 -norm for the errors and the efforts of the control laws on the altitude movement

Adaptive mechanism	Altitude [m]	
	$\mathcal{L}_2[e_h]$	$\mathcal{L}_2[\delta_e]$
MIT	1.2949	0.2876
MIT-SM	1.2913	0.2689
MIT-2SM	1.0856	0.2362
MIT-HOSM	1.0773	0.2519

The simulations results for the altitude control applying the MIT rule [9], are presented in the Figure 2, in the upper graphic of the Figure 2 is presented the response of the MIT rule and in the lower graphic of the same figure, shows the controller response.

Analyzing the results obtained in the Table 1 is appreciated that the PD controller with the adaptive mechanism based on the MIT rule has presented more error than the MIT with the sliding mode theory, that is, the MIT rule is 0.278%, 16.1635% and 16.8044% bigger than MIT rule with sliding mode (MIT-SM), the MIT rule with two sliding modes (MIT-2SM) and the MIT rule with high order sliding mode (MIT-HOSM), respectively.

Meanwhile, the PD control effort with the MIT rule is bigger than the other technique in the study, that is, with the adaptive mechanism by the MIT rule, the PD control effort is 6.5021%, 17.8721% and 12.4131% bigger than the MIT-SM, the MIT-2SM and the MIT-HOSM, respectively (see the Table 1). On the other hand, the error of the PD controller with the adaptive mechanism based on the MIT rule with the sliding mode is 15.9297% bigger than the MIT-SM and is 16.5725% bigger than the MIT-HOSM. The results obtained with the adaptive mechanism based on MIT rule with sliding mode are presented in the Figure 3, where the upper graphic of the same figure we can appreciate the convergence to the desired values in spite of the noise applied in the control system.

In Table 1 we can see that the PD controller with the adaptive mechanism based on the MIT rule with sliding mode applies a control signal 12.1607 bigger than the adaptive mechanism based on the MIT rule with

two sliding modes (MIT), and even the adaptive mechanism with the MIT rule with the sliding mode the control effort is 6.3221% bigger than the MIT-HOSM. In the lower graphic of the Figure 3 is shown the control signal generated by the PD with the adaptive mechanism based on the MIT rule with the sliding mode.

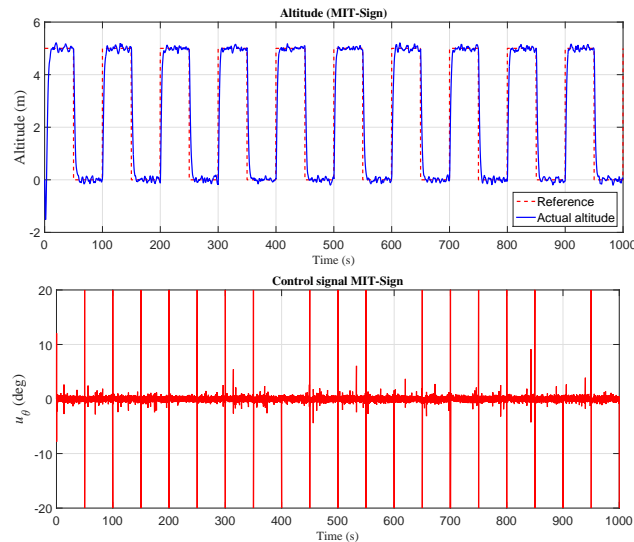


Figure 2. Adaptive mechanism based on the MIT-rule with sign function

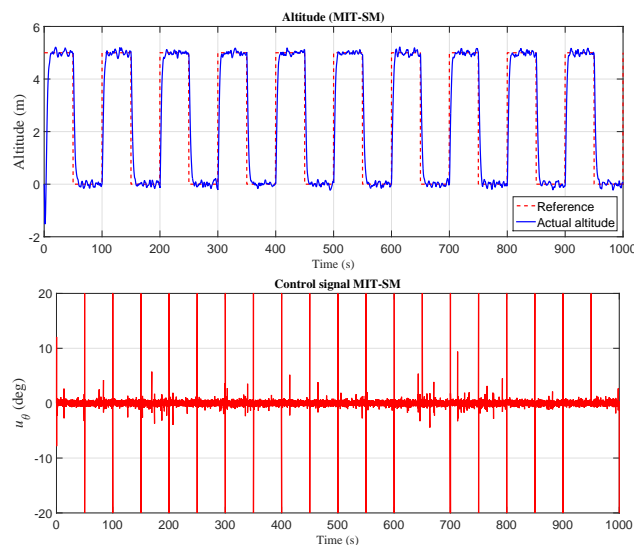


Figure 3. Adaptive mechanism based on the MIT-rule with sliding mode

Figure 4 is presented the results obtained by the PD controller based on the MIT-2SM, in the upper graphic is appreciated the response of the PD controller with the adaptive mechanism based on the MIT-2SM.

In Table 1 we can see that the PD controller based on the MIT-2SM has presented an error 15.9297% bigger than the MIT-HOSM, but the adaptive mechanism based on the MIT with two sliding modes has presented a PD control effort 6.2327% smaller than the MIT-HOSM. In the lower graphic of Figure 4 is presented the response of adaptive mechanism based on the MIT rule with two sliding modes.

Meanwhile, the response of PD controller with the adaptive mechanism based on the MIT-HOSM is presented in Figure 5, in the upper graphic of the same figure is shown the convergence to the desired values and in the upper graphic is presented the controller response.

The PD controller based on the MIT-HOSM has a lower error in comparison with the other adaptive mechanisms presented in this work and even presents a smaller control action when is compared with the PD controller with the adaptive mechanism based on the MIT rule and with them based on the MIT rule with sliding mode. An exception occurs when it is compared with the adaptive mechanism based on the MIT rule with two sliding modes (see Table 1). And finally, the advantage of using the PD controller with the adaptive mechanism based on the MIT rule with high order sliding mode is the reduction in the undesired chattering effect in the control signal, the evolution of the chattering reduce even with the perturbation in the system, this can be appreciated in the Figure 6.

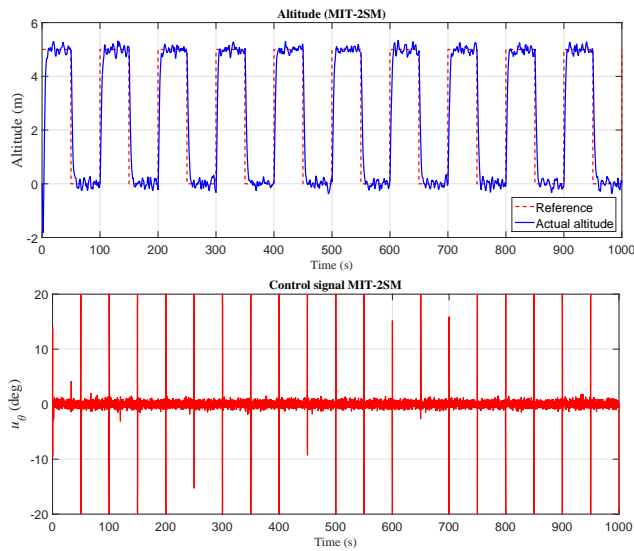


Figure 4. Adaptive mechanism based on the MIT-rule with two sliding mode

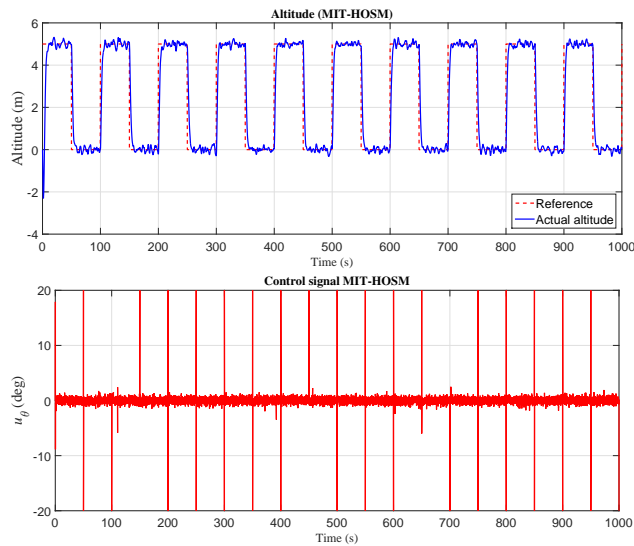


Figure 5. Adaptive mechanism based on the MIT-rule with HOSM

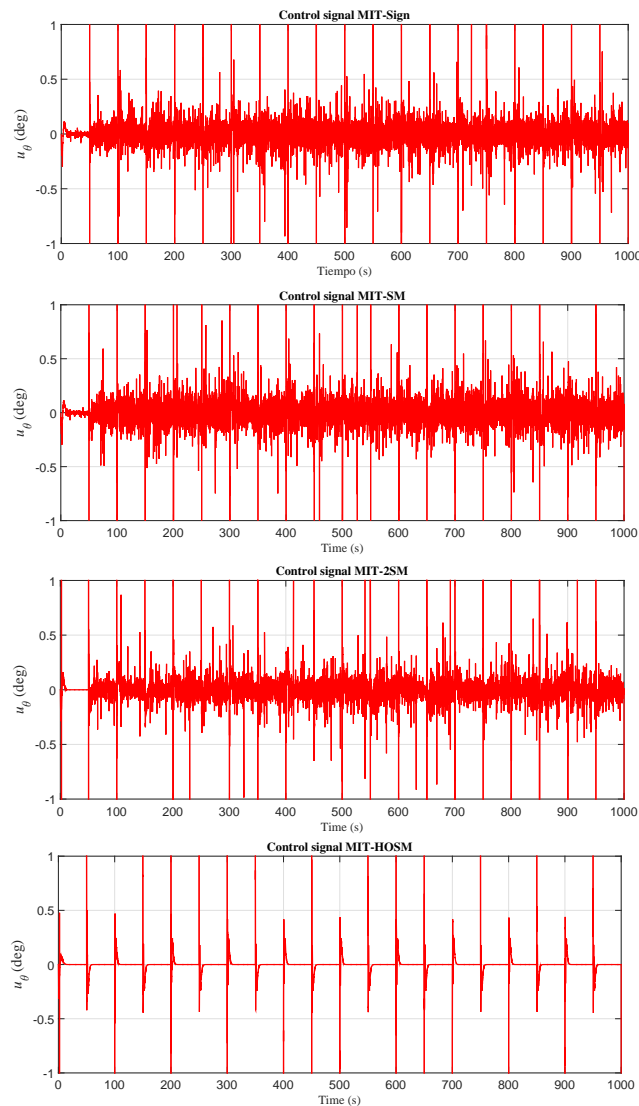


Figure 6. Control signals zoom

5. CONCLUSION

The adaptive mechanism based on the MIT rule presented an error and control effort bigger than the MIT rule with the sliding mode techniques. Despite it, the adaptive controller with the MIT rule as an adaptive mechanism for the controller gains achieves the desired altitude. The adaptive mechanism based on the MIT rule with high order sliding mode has presented a better performance than the other adaptive mechanisms presented in this work, considering that the altitude error is the smallest. Even this adaptive mechanism for the PD controller has presented less control effort than the adaptive mechanisms based on the MIT rule and MIT rule with sliding mode. The PD controller with the adaptive mechanism based on the MIT rule with high order sliding mode has presented a considerable reduction of the chattering effect. The future work consists of the implementation (real-time flight tests) of this technique in a miniature aerial vehicle to analyze the performance of the PD controller with the adaptive mechanisms proposed in this work.

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