INTERVAL TYPE-2 FUZZY CONTROLLER BASED ON SLIDING MODE CONTROL FOR ROBOT ARM DRIVEN BY ARTIFICIAL MUSCLES

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Abstract: In this paper, we propose the application of an Interval Type-2 Fuzzy Sliding Mode Controller IT2FSMC for 2 degrees of freedom robot arm actuated by pneumatic artificial muscles (PAM). A robust IT2FL controller based on the Lyapunov stability condition of sliding mode control SMC was adopted. The objectives of the control are: (1) to avoid the modelling problem in this type of robot, (2) to attenuate the chattering effect of the SMC, (3) to reduce the rules number of the fuzzy control, (4) to guarantee the stability and the robustness of the system and (5) to handle the uncertainties of the system. First joints of robot are approximated by adequately linear differential equations; next we present the proposed IT2FSM approach of control. In the last, this method has experimented and compared to an interval type-2 fuzzy controller IT2FC in order to demonstrate its effectiveness.

1 INTRODUCTION

In the last years, some precision robotic tasks based on the pneumatic artificial muscle (PAM) actuators have been used (Lilly et al, 2005); (Lopez et al., 2006); (Schmitt et al., 2007). The (PAMs) are tubular pull-actuators with a special fibber arrangement. The fibres form a diamond pattern in a three-dimensional mesh structure, which allows the actuator to contract when the internal pressure of the hose is increased (Schmitt et al, 2007). Several examples of (PARM) based robot arm can be cited, for example: Lucy humanoid robot of the Bruxel University (Verrelst, 2005) ISAC humanoid robot of (Schröder et al, 2003.), the seven degrees of freedom (7-DOF) robot manipulator of the INSA laboratory (Tondu, 2007; Tondu, et al, 2009) and that of FESTO company (Pomiers, 2003) and so on. These systems present same advantages such as cheapness, light weight, compliance and low power/weight. In the opposite, because of the time varying inertia, hysteresis and joints friction (Lopez et al, 2006), the (PAMs) robot's Arm belongs to the class of highly nonlinear systems, where perfect known of their parameters using conventional modelling techniques is very delicate. For this raison currently, the major challenge in pneumatic muscle applications is to have a robust control. Several robust controls are applied to the robot with artificial muscles, we can mention: Sliding Mode Control (SMC) (Lopez et al., 2006), Higher Order Sliding Mode Control (HOSM) (Tondu et al., 2009) nonlinear control (Xiang, 2001) and so on.

In the last few years, a new approach of the Fuzzy Logic (FL) called Type-2 fuzzy logic (T2FL). This type of fuzzy logic is firstly introduced by L. Zadeh in 1975 (Castillo et al., 2008). The (T2FL) is the generalization of the classical type-1 fuzzy logic. Type-2 fuzzy sets is characterized by membership grades that are themselves fuzzy (Wu et al., 2006). The membership function (MF) of a type-2 fuzzy set has a footprint of uncertainty (FOU), which represents the uncertainties in the shape and position of the type-1 fuzzy set (Castillo et al., 2008); (Wu et al., 2006). The T2FL is given for handle the uncertainties in the systems (Castillo et al., 2008).

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Sliding Mode control (SMC) and Fuzzy Logic (FL) are attractive control methods used in the cases when we have a process that is difficult to model. Fuzzy Sliding mode control (FSMC) is the combination of the sliding mode control and the fuzzy logic techniques. The objectives of this combination are: (1) to decrease the chattering effect caused by the discontinuous part of the SMC, and (2) to reduce significantly the rules number of the (FL) part. (FSMC) guaranteed more robustness compared to the parameters, modelling uncertainties and external disturbances. A little number of combination of the (SMC) and the (IT2FL) exist in the literature, for example: inverted pendulum and Duffing dynamical system (Hsiao, 2008), SISO nonlinear systems (Lin et al., 2010) chaotic system (Roopaei et al., 2010); (Hwang et al., 2011).

This paper presents the experimental study of the robust interval type-2 fuzzy sliding mode controller for 2-DOF robot arm actuated by pneumatic artificial muscles. This control scheme allows us to avoid the nonlinear modelling problems and guaranteed the stability and the robustness of the robot.

For the best presentation of the work, the paper is subdivided to five sections. After the introduction, section two presents the 2-DOF robot arm and its identification. Section three explains sliding mode control and the type-2 fuzzy control. The proposed controller with the reasoning method will be the objective of section four, experimental results and discussion are presented in the section five. Finally the paper is closed by the conclusion.

2 ROBOT DESCRIPTION AND PARAMATERS IDENTIFICATION

2.1 Robot Description

The 2-DOF of the robot actuated by the pneumatics muscles called McKibben muscles is presented in the figure (1). This system is Robosoft product dedicated to research and development actions (Pomiers, 2003). We have chosen this robot for the reason that is suitable for domestic's application. The used robot presented in figure 1 is composed by several elements such as: (1) 4 FESTO fluidic muscle, (2) 4 FESTO Proportional directional control valve (3) 4 FESTO Pressure sensor, (4) 1 FESTO High-Flow D-Series Pneumatic Filters (5) 1 FESTO High-Flow D-Series Pneumatic Regulators (6) 1 FESTO High-Flow D-Series Pneumatic Lubricators Economical (7) 1 FESTO Branching module (8) 1 FESTO Soft-start valve and (9) 1 FESTO Distributor block (Pomiers, 2003). The each joint has 0.819 *m* of langue, and robot weight is around of 15 Kg. The robot must be used at ambient operating temperature of 0- 45°C.

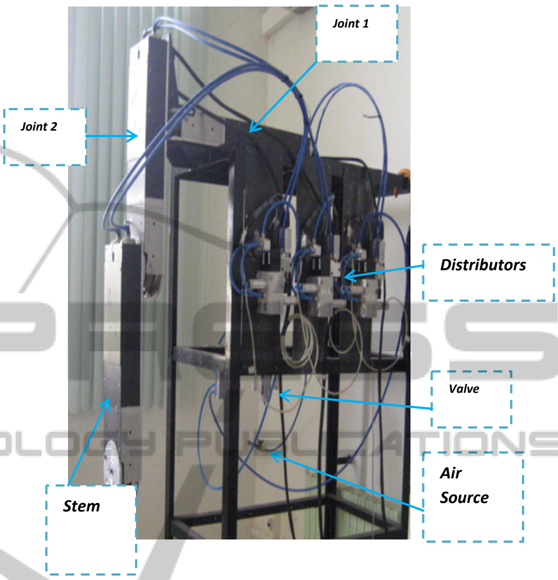


Figure 1: 2-DOF robot arm actuated by the muscles.

As in skeletal muscles, two actuators are needed to be coupled in order to generate a bidirectional motion, one for each direction. This mechanical motion can be obtained by modifying the pressure ΔP in each muscle. The motion principle is shown in Figure 2.

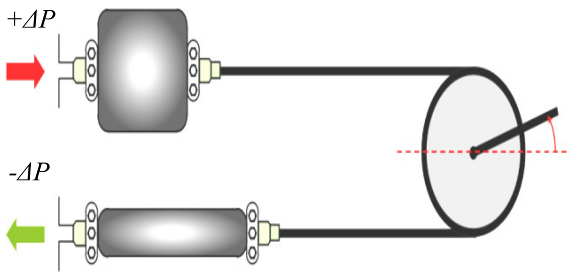


Figure 2: 1-Link arm robot actuated by the muscles.

Depicted in the figure 3, the robot control system is composed by four subsystems so: in addition of the robot, there exist a computer PC using for including the program of control, a control box CB charged for the communication between the PC and the robot. The robot, PC and CB are connected by CAN bus, finally the Air distributer is used as alimentation of the robot.

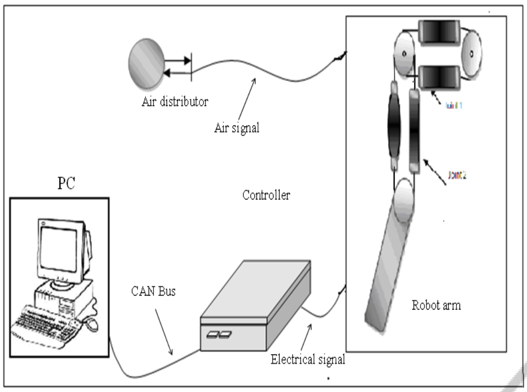


Figure 3: 1-Link arm robot actuated by the muscles.

2.2 Control Problems

In addition to the well known problems of robots with PAM such as: hysteresis, joint friction and time varying, in the case of our robot arm, there exist many difficulties affect its control. We can give: The pressure in each muscle is not identical. The antagonistic system is affected by the temperature and volume variations. The flow of each distributor is supposed to be identical, but really they can have a little difference from one to the other, the characteristics of a muscle change slightly when the number of operating cycle increases, these phenomena's will change the characteristics of the system behaviour, i.e. the parameters of the system are not exactly known and the modelling errors may be appeared.

2.3 Robot Modelling and Parameters Identification

The dynamic equations of n degrees of freedom mechanical system using of the Lagrange equations can be written as follow (Schmitt et *al*, 2007):

$$\frac{d}{dt}\left(\frac{\partial L(q,\dot{q})}{\partial \dot{q}}\right)-\frac{\partial L(q,\dot{q})}{\partial q}=\Gamma(u) \tag{1}$$

Where q denote the generalized coordinate vector, $\dot{q}$ denote the generalized velocity vector and t denote the generalized force vector. $L(q,\dot{q})$ Is the Lagrange function which is the difference of kinetic energy and potential energy. The application of the Lagrange equation for the robot system led to the following general equation (Lopez et *al*, 2006):

$$J\ddot{q}+h(\dot{q})+g(q)=\Gamma(u) \tag{2}$$

Where q, $\dot{q}$ and $\ddot{q}$ are respectively the angular position, velocity and acceleration vectors, J is the inertial related matrix, $h(\dot{q})$ is the vector of centrifugal, coriolis and friction terms. $g(q)$ is the vector of gravity terms and $\Gamma(u)$ is the torque input vector, u is the vector of control.

For one axis, the coriolis forces due to the interaction with other axis do not exist and the centrifugal force present a null couple compared to the axis of rotation. By considering gravity and viscous frictions dominating, the equation of the movement can always be written in the following nonlinear form (Lopez et al, 2006):

$$J\ddot{q}+C(\dot{q})\cdot\dot{q}+G(q)\cdot q=\Gamma(u) \tag{3}$$

With: $h(\dot{q})=C(\dot{q})\cdot\dot{q}$, $g(q)=G(q)\cdot q$

The movement equation can be rewritten as:

$$\ddot{q}+J^{-1}\cdot C(\dot{q})\cdot\dot{q}+J^{-1}\cdot G(q)\cdot q=J^{-1}\cdot\Gamma(u) \tag{4}$$

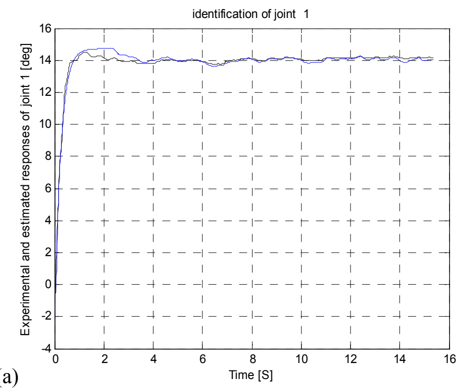
Within a linear approximation, the equation (2) can be written, assuming that the derivatives of the entry are not involved (Lopez et al, 2006):

$$\ddot{q}+A_1\cdot\dot{q}+A_0\cdot q=BU \tag{5}$$

Where $A_1=J^{-1}\cdot C(\dot{q})\cdot$, $A_0=J^{-1}\cdot G(q)$ and $BU=J^{-1}\cdot\Gamma(u)$ are parameters of the robot model that should be identified. The linear approximation was too the objective of the work of (Tondu, 2007) for two articulations of 7–DOF robot manipulator.

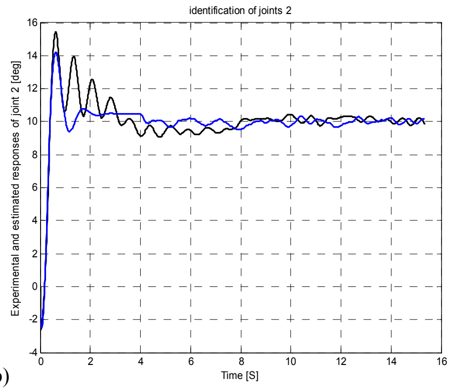
For the determination of the best linear model, the dynamic behavior of the robot joints were characterized by Pseudo Random Binary Sequence (PABS) inputs, which is a popular signal used in the identification of systems. The (PABS) is characterized by its large spectrum of frequencies. The adequate (PABS) is injected and result joint angular displacement values output responses are saved.

The following figures represent the experimental results of the identification of the robot's Joints:



(a)

Figure 4: Identification of the joint one (a) and joint two (b) respectively.



(b)

Figure 4: Identification of the joint one (a) and joint two (b) respectively. (cont.)

The graph of the model validation is illustrated in Figure (4). The bleu lines represent the approximated models responses and the black lines are the real system outputs.

The corresponding polynomial parameters of each joint are given by:

$$A_0 = diag\ (a_{01}, a_{02}) = diag\ (7.8573, 16.2075)$$
$$A_1 = diag\ (a_{11}, a_{12}) = diag\ (5.6654, 2.9595)$$
$$B = diag\ (b_1, b_2) = diag\ (15.3217, 2.0194)$$

From these results, the robot arm may be presented in the state space linear multivariable equations:

$$\dot{X}(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ -7.8573 & -5.6654 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -16.2075 & -2.9595 \end{bmatrix} X + \begin{bmatrix} 0 & 0 \\ 15.3217 & 0 \\ 0 & 0 \\ 0 & 2.0194 \end{bmatrix} U(t) \quad (6)$$

$$Y(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} X$$

It is very important to say that the obtained linear model is not representative of the real robot. But, this linearization is used in transitory step for objective to apply the sliding mode control (SMC). The SMC technique is very knowledge by its robustness compared to systems poorly modeled and/or has parameter variations, and/or external disturbances.

3 INTERVAL TYPE-2 FUZZY SLIDING MODE CONTROL DESIGN

We divided this part in two steps. In the first one, we design the conventional sliding mode control and an interval type-2 fuzzy control, while the second proposes the fuzzy sliding mode control approach for the robot arm control.

3.1 Sliding Mode Control

A Sliding Mode Control is a Variable Structure Control (VSC). Basically, VSC includes several different continuous functions that map plant state to a control surface. The switching among these functions is determined by plant state which is represented by a switching function (Xiang, 2001). For the best presentation of the SMC, we considering the MIMO system described by the following state-space equation (Xinghuo et al, 2009):

$$\dot{X}(t) = F(X) + BU(t) \quad (7)$$

Where: $X(t)$ is the vector of state variables, $F(X)$ is the vector of the non-linear equations of the system, B is the input matrix and $U(t)$ is the vector of control. The design of the sliding mode control needed two steps.

3.1.1 The Choice of the Sliding Surface

The selected sliding surface for a MIMO system given in (7) is generally obtained by (Xinghuo et *al*, 2009):

$$S(X,t) = G\left(X^d(t) - X(t)\right) - \phi(t) - S_a(X) \quad (8)$$

Where: $\phi(t) = GX^d(t)$, $S_a(t) = GX(t)$ and G is a diagonal gain matrix.

The sliding surface is given usually by the following linear hyper-plan function:

$$S(X,t) = \begin{bmatrix} S_1 \\ \vdots \\ S_n \end{bmatrix} = \begin{bmatrix} e_1 + \lambda_1 \cdot \dot{e}_1 \\ \vdots \\ e_n + \lambda_n \cdot \dot{e}_n \end{bmatrix} \quad (9)$$

Where λ_i with $i = 1 \cdots n$ are constant positive values.

Once the function of commutation is calculated the problem of tracking need the conception of the law control with the stat vector $X(t)$ rested on the sliding surface. In this case $S(X,t) = 0$ for only $t \geq 0$. A suitable control U has to be found so as to retain the error $e(t)$ on the sliding surface. To achieve this purpose, a positive Lyapunov function V is defined as:

$$V(s) = \frac{S^T S}{2} \quad (10)$$

The sufficient condition for the stability of the system is given by:

$$\frac{dV(s)}{dt} = -S^T D\, sign\,(S) \leq 0 \quad (11)$$

Where D is the positive-definite diagonal gain matrix.

3.1.2 Control Law Design

The sliding mode control comports two terms which are equivalent control and switching control:

$$U(t) = U_{eq}(t) + U_s(t) \quad (12)$$

$U_{eq}(t)$ Is the equivalent term of the sliding mode control, i.e. the necessary known part of the control system when $\dot{S} = 0$, and it is gevin by the following equation:

$$U_{eq}(t) = -(GB)^{-1}\left(GF(X) - \frac{d\phi}{dt}\right) \quad (13)$$

$U_s(t)$ Describes discontinues control part where it is given by:

$$U_s = (GB)^{-1} D.sign(s) = Ksign(S) \quad (14)$$

In our case of control, we choose to not use the equivalent control of the robot. We uses only the discontinuous part of control given by equation (14), this choose is imposed by the parameters variation of the not possibility to its estimation exactly. The equivalent control part will be compensated by the interval type-2 fuzzy controller will be presented in the later section of this paper.

3.2 Interval Type-2 Fuzzy Control

The idea of a type-2 fuzzy set (T2FS) was introduced in (1975) by Prof. Zadeh (Castillo et al, 2008). This fuzzy set is an extension of the ordinary fuzzy set named type-1 fuzzy logic set. The use of (T2FS) is called type-2 Fuzzy Logic Systems (T2FLSs), which are useful especially in the cases where it is difficult to determine an exact and precise (MF) and/or the measurement of uncertainties is difficult or even impossible**.** By including the footprint of uncertainty (FOU) the (MFs) of the (T2FSs) become three dimensional forms. The (FOU) provides an additional degree of freedom to make it possible to directly model and handle uncertainties (Castillo et al, 2008); (Wu et al., 2006).

Theoretically, an interval type-2 fuzzy set (IT2FS) $\tilde{A}$ in X is characterized as (Castillo et al, 2008; Wu et al., 2006):

$$\tilde{A} = \int_{x\in X} \int_{u\in J_x \subseteq [0.1]} 1/(x,u) = \int_{x\in X} \left[\int_{u\in J_x \subseteq [0.1]} 1/u \right] / x \quad (15)$$

Where, $\iint$ denotes the union over admissible variables x and u, $x \in X$ is the primary variable, $u \in J_x$ is the secondary variable, $J_x \subseteq [0,1]$ is the primary MF of x, for interval type-2 sets the secondary grades of $\tilde{A}$ all equal to 1 (Wu et *al.*, 2006).

The interval type-2 fuzzy controller consists of: fuzzifier, an inference engine, rules base, type reduction and a defuzzyfier. Rules may be provided by an expert (i.e. a human).

Fuzzyfier: The fuzzifier maps a crisp input into a type-2 fuzzy set $\tilde{A}$.

Rules: The structure of rules in a type-1 FLS and a type-2 FLS is the same, but in the latter the antecedents and the consequents will be represented by type-2 fuzzy sets (Wu et al., 2006). The general IF-THEN rules in this case is given by (Castillo et al, 2006).

$$R^i : IF\ x_1\ is\ \tilde{F}_1^i\ And \cdots And\ x_p\ is\ F_p^i\ Then \quad u\ is\ \tilde{G}_1^i \quad (16)$$

Fuzzy Inference Systems: Type-2 Fuzzy Inference Systems can be used when the circumstances are too uncertain to determine exact membership grades (Cazarez-Castro et al. 2010). From the IT2FS point of view, the fuzzy rule in (16) can be written as (Castillo, 2008):

$$R^i : \tilde{F}_1^i \times \cdots \times \tilde{F}_p^i \longrightarrow \tilde{G}^i \quad (17)$$

From the IT2MF point of view, (17) is equivalent to

$$\mu_{R^i}(e,u) = \cup_{a=1}^{p} \mu_{\tilde{F}_a^i}(e_a) \cap \mu_{\tilde{G}^i}(u) \quad (18)$$

where u denotes the Meet operation, p is the number of input variables, and up $\cup_{a=1}^{p} \mu_{\tilde{F}_a^i}(e_a) \equiv \tilde{F}(e)$, which results in an interval set described by (Tsai et *al.*, 2008) :

$$\tilde{F}(e) = \left[\underline{f}^i(e), \overline{f}^i(e)\right] \quad (19)$$

Where $\underline{f}^i(e)$ and $\overline{f}^i(e)$ be re-expressed as:

$$\begin{aligned} \underline{f}^i(e) &= \underline{\mu}_{\tilde{F}_1^i}(e_1) * \underline{\mu}_{\tilde{F}_1^i}(e_2) \\ \overline{f}^i(e) &= \overline{\mu}_{\tilde{F}_1^i}(e_1) * \overline{\mu}_{\tilde{F}_1^i}(e_2) \end{aligned} \quad (20)$$

Where * denotes the product operation.

Type-reducer: The type-reducer generates a type-1 fuzzy set output, which is then converted in a crisp output through the defuzzifier. This type-1 fuzzy set is also an interval set, for the case of our FLS we used center of sets (cos) type reduction, $U_{\cos}(e)$ which is expressed as (Castillo et al, 2008); (Wu et al. 2006).

$$U_{\cos}(e) = [u_l, u_r] = \int_{u^1 \in [u_l^1, u_r^1]} \cdots \int_{u^M \in [u_l^M, u_r^M]} \int_{f^1 \in [\underline{f}^1, \overline{f}^1]} \cdots \int_{f^M \in [\underline{f}^M, \overline{f}^M]} 1 \Big/ \frac{\sum_{i=1}^{M} f^i u^i}{\sum_{i=1}^{M} f^i} \qquad (21)$$

Defuzzifier: the average of u_r and u_l, so the defuzzified output of an interval singleton type-2 FLS is (Castillo et *al*, 2008; Wu et *al.*, 2006):

$$y = \frac{u_r + u_l}{2} \qquad (22)$$

3.3 Interval Type-2 Fuzzy Controller based on Sliding Mode Control Design

To realize the robust IT2FLC, we choose a decentralised type-2 fuzzy controller with two inputs and one output for each joint. The inputs of the controller are the siding surface and its derivatives' ($S_i = e_{i1} + \lambda_{i1} \cdot \dot{e}_{i1}$ and $\dot{S}_i$), the output is the control law (u_{fuzzy}) which should be applied to the muscles. The membership functions of the fuzzy inputs variables are chosen to be fully overlapped, triangular, trapezoidal and symmetric for the upper and lower membership functions. These (MFs) are presented in the following figures:

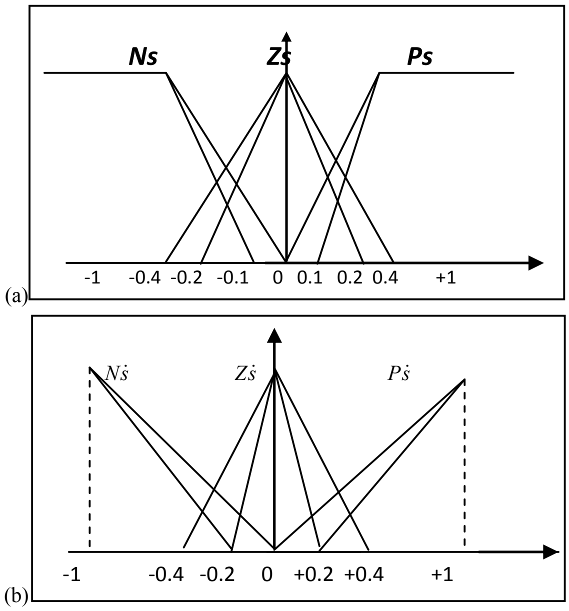


Figure 5: Inputs fuzzy controller (a) the sliding surface and (b) its variation.

The following figure present the output MF distributed on discourse universes. There are three Type-1 MFs (N negative, Z zero, and P positive). We choose Type-1 (MFs) in the objective to reduce the time of fuzzy control computing:

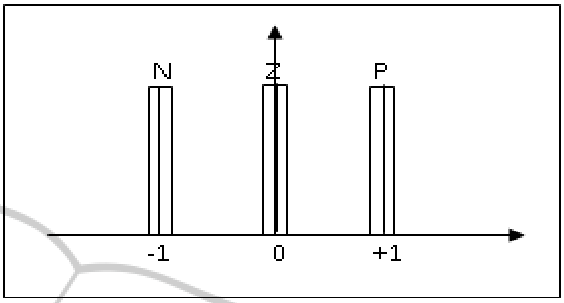


Figure 6: Output singleton membership functions.

Based on the stability conditions given in the general form by the equation (11), we can be led to the diagonal type of If-Then reasoning rules (Castillo, 2008), where through that we can able to guarantee the stability of the global system. Following table present our reasoning:

Table 1: Rule base.

S \ $\dot{S}$	***N***	***Z***	***P***
P	***Z***	***PM***	***P***
Z	***NM***	***Z***	***PM***
N	***N***	***NM***	***Z***

The inference engine is the core of the fuzzy system which handles the way in which rules are combined. We used the general equation (20) to realize the inference step.

In this paper, we are computing a Centroid type-reducer method given by the equation (21). From the type-reducer we obtain an interval set *Ucos*, must be defuzzifier it.

The defuzifier is the last step of a type-2 fuzzy control the output of the defuzzier is the crisp value should be injected to the actuators of the robot arm, the equation (22) is used to comput this value.

The full feedback control diagram of the IT2SMC for the robot arm with PAM is presented in the following figure:

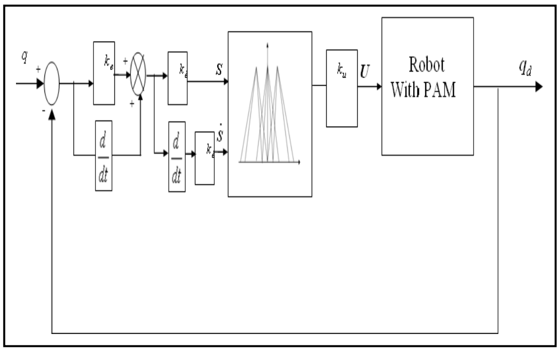


Figure 7: IT2 FSMC control for the robot with PAM.

4 EXPERIMENTAL RESULTS AND DISCUSSES

Experimental results are used to examine the feasibility and the validity of the proposed type-2 fuzzy sliding controller. The experimental are accomplished by the implementation in C language on the Pentium 4 PC. In order to handle efficiently such a distributed architecture, the software system is under Linux with an RTAI module and Syndex as an interface more detailed has given in (Pomiers, 2003).

The regulation mode was adopted to test the capability of the proposed controller to maintain the imposed performances and the robustness. We want that the 2-DOF robot attend the desired angular position of 14 degree for the joint one and 10 degree for the joint 2, with the initial position of zero degree for all joints. We choose to present the joints responses, the control signal and the inputs variables (sliding surfaces) to show the attenuation of the charting effect for the all joints of the robot arm. Figure 6 present the experimental results for the control of the joint 1. Figure 7 gives the experimental results obtained by the application of the IT2FSMC. The fuzzy sliding mode controller was implemented with a sampling time of 10 ms. In the way of comparison, we used the IT1FSMC as reference. The interval type-2 fuzzy logic controller is used for objective to compare with the proposed IT2SMC controller. The inputs of the IT2FC were the error on angular position and its derivative. The output in the pressure should be injected in the each joint of the robot. The membership functions of the IT2FC are similar with IT2FSMC.The following figures present the results of joint 1.

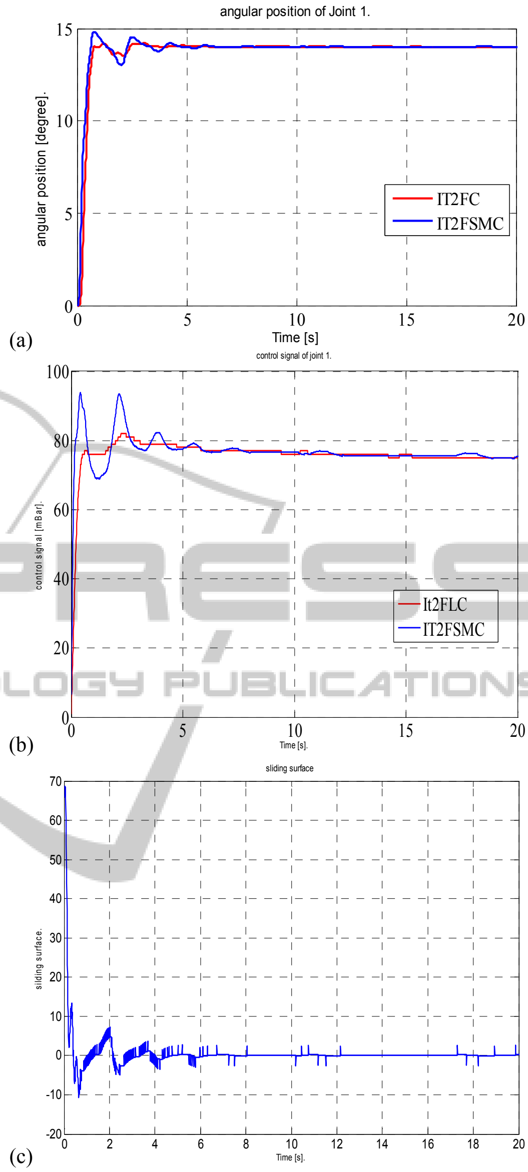


Figure 8: (a) joint one angular position response for the IT2FSMC (bleu) and IT2FC (red), (b) control signal for the IT2FSMC (bleu) and IT2FC (red) and (c) the surface variation.

For the IT2FSMC, we observe from the position response curvature that the joint one tracked adequately the imposed reference angle, with the existence of satisfactory static and dynamic errors. We can see from the figures of the control signal like that of sliding surface the smoothes signals, and then the chattering effect is attenuated. As the IT2FSMC as IT2FC present the good results, however, the IT2FSMC has the little Amelioration.

The control of the joint two is very difficult compared to the joint one. We observe from the

position response of the IT2FSMC that the joint two tracked adequately the imposed reference angle, with the existence of acceptable static and dynamic errors. This joint present delay may be caused by the gravitational effect. In the other hand we can see from the figures of the control signal like that of sliding surface the smoothes signals, which presents the attenuation of the chattering effect. In the opposite the IT2FC has not given the good results. We can say that the IT2FSMC has given the better results compared with the IT2FC specifically it is shown in the joint 2.
The following figures present the results of joint 2:

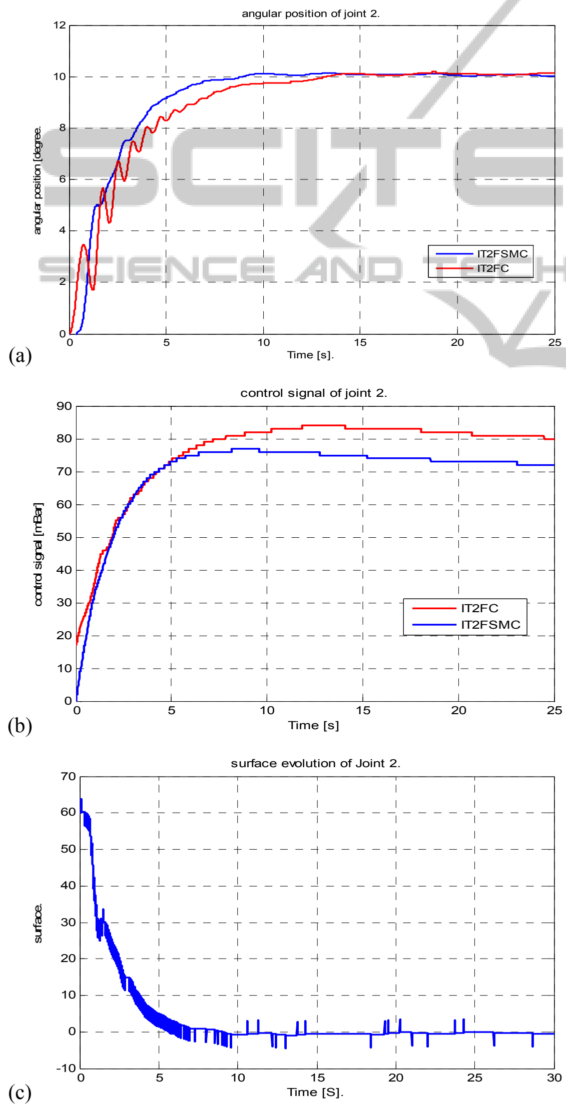


Figure 9: (a) Joint two angular position response for the IT2FSMC (bleu) and IT2FC (red), (b) Control signal for the IT2FSMC (bleu) and IT2FC (red) and (c) The surface variation.

5 CONCLUSIONS

In this paper, an interval type-2 fuzzy controller based on stability condition of the sliding mode control for robotic arm actuated by artificial muscles is proposed. This controller was implemented on real time to the 2- DOF arm robot, to control of its angular positions with a very little number of rules. The experimental results shows that not only the good tracking performance has been obtained, but also the stability and the robustness have guaranteed with a chattering effect have avoided. The proposed IT2FSMC present superior performances compared with an IT2FC. In future work, we will compare this control approach with an others control techniques.

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