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Experimental Study of Nonsingular Terminal Sliding Mode Controller for Robot Arm Actuated by Pneumatic Artificial Muscles

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Abstract: In this paper, experimental study of robust control for robot manipulator actuated by pneumatic artificial muscles was realized. The experimented controller belonged to the class of variable structure systems which is called nonsingular terminal sliding mode (NTSM). The control approach is based on the time delay estimation method. First, the nonsingular terminal sliding mode control approach was presented and the stability of the system in closed loop was analyzed using Lyapunov stability theorem. Second, in order to show the efficiency and the superiority of the proposed approach, experimental results are presented in regulation and trajectory tracking modes using 2-DOF robot manipulator actuated by pneumatic artificial muscles. Third, the controller robustness was tested.

1. INTRODUCTION

Sliding Mode Control (SMC) is a well-known as a discontinuous feedback control technique which has been exhaustively explored in many works by many authors (V.I. Utkin 1992 and J.J. Slotine 1984). Sliding mode controllers are powerful tools to robustly control uncertain system. They are able to achieve finite time reaching and exact keeping of a suitably chosen sliding manifold in the state space by means of a discontinuous control. One of the main features of sliding mode control is their robustness with respect to certain external perturbation inputs affecting the system behavior. Indeed, standard sliding mode controllers can only deal with systems having relative degree equal to one. In addition, they can induce undesirable chattering effects, i.e. high frequency oscillations of the controlled variable, which cannot be tolerated in some practical applications (Chettouh et al.2008 and Braikia et al.2011) (experimental set).

Terminal Sliding Mode Control (TSMC) is a specific case of the SMC, which is characterized by a nonlinear sliding variable (S. L. Tzuu-Hseng and H. Yun-Cheng 2010). TSMC offers several properties such as: (1) Able to achieve a finite time convergence of the controlled systems, (2) Give a fast convergence and good dynamic responses, (3) TSMC is particularly useful for high precision control because of the feature of the speeding up the rate of convergence near the equilibrium point, (4) TSMC is also available for control of second or higher nonlinear uncertain systems (S. L. Tzuu-Hseng and H. Yun-Cheng 2010). In the opposite, TSMC has the singularity disadvantage. This last problem is surmounted by the proposition of the Nonsingular Terminal Sliding Mode Control (NTSMC) (S. L. Tzuu-Hseng and H. Yun-Cheng 2010 and Rezoug et al.2011). As SMC as NTSMC have the chattering drawback. In order to solve the chattering drawback, many solutions have been proposed (S. L. Tzuu-Hseng and H. Yun-Cheng 2010 and Rezoug et al.2011). In our case we have tested the traditional method consists on the replacement of discontinues part by the saturation function.

In other hand, Pneumatic Artificial Muscles (PAMs) have drawn increasing interest from many robotic applications in recent years, spreading from musculoskeletal robots to rehabilitation robots (Amato et al.2013). This interesting about PAMs is caused by their several advantages such as: inherent damping, variable stiffness, high power/weight ratio and structural flexibility, etc. In robotic control domain, the modeling of the studied robot is an important step. However, in large cases of robotic systems obtaining exact model is not always available. The modeling drawback will be increased in the case of robots actuated by PAMs, which are present a strong nonlinearity caused by several difficulties among them: hysteresis, time friction and parameter changes (Rezoug et al.2012), etc. In order to deal with the model uncertainties due to parameter variability and limited knowledge of the robot dynamics, the use of robust control approaches is required. Then the major challenge for these systems is to have the robust control. Several robust control methods have been used for robots with PAMs, such as, Optimal Control (Amato et al.2013), Artificial Intelligence Control (Fuzzy Logic, Neural Networks, etc.) (Rezoug et al.2012 and T. Leephakpreeda 2011), Sliding Mode Control (J. H. Lilly and L. Yang 2005), their combinations (Rezoug et al.2012 and J. H. Lilly and L. Yang 2005) and so on.

In this work, we have examined experimentally a robust, stable, smooth and fast controller called Nonsingular Terminal Sliding Mode Controller (NTSMC). Using the Time Delay Estimation Method (TDE) the modeling step is not needed for controlling the robot manipulator with PAMs.

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Real experimentations using the robot arm of INSA of Toulouse France (Tondu et al.2005) were realized.

The rest of the paper is organized as follow: in section two, we present the NTSMC base on the TDE method for n-DOF robot manipulator actuated by PAMs. Section three presents the real experimentations with and without additional load of the proposed controller and finally the paper is closed by conclusion.

2. DESIGN OF TERMINAL SLIDING MODE FOR *N*-LINK MANIPULATOR ROBOT WITH PAM

The general dynamic equation of n-DOF robot manipulator with PAMs is given as:

$$\mathbf{M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(q,\dot{q}) + T_d} = \boldsymbol{\tau} \tag{1}$$

Where:

- $\mathbf{M(q)} \in \mathbf{R}^{\mathbf{nxn}}$ is the inertial symmetric positive matrix, e.g. non-singular and bounded.
- $\mathbf{C(q,\dot{q})} \in \mathbf{R}^{\mathbf{nxn}}$ is the vector of Centrifugal, Coriolis.
- $\mathbf{F(q,\dot{q})} \in \mathbf{R}^{\mathbf{nx1}}$ is Friction vector.
- $\mathbf{G(q)} \in \mathbf{R}^{\mathbf{nx1}}$ is the vector of gravity.
- $\mathbf{q} \in \mathbf{R}^{\mathbf{nx1}}$, $\mathbf{\dot{q}} \in \mathbf{R}^{\mathbf{nx1}}$ and $\mathbf{\ddot{q}} \in \mathbf{R}^{\mathbf{nx1}}$ are the position, velocity and acceleration vectors, respectively.
- $\boldsymbol{\tau} \in \mathbf{R}^{\mathbf{nx1}}$ Is the torque input vector, and $\mathbf{T_d} \in \mathbf{R}^{\mathbf{nx1}}$ are the unknown bounded disturbances i.e. $\|\mathbf{T_d}\| < \boldsymbol{\beta}_\mathbf{d}$, with $\boldsymbol{\beta}_\mathbf{d}$ is a positive vector of $\mathbf{q}$ [2].

Let the diagonal matrix with constant real values $\mathbf{\overline{M}} = \mathbf{diag(m_{ii})}$ with $\mathbf{i=1\ldots n}$ (Tao et al.2013).

Substituting $\mathbf{\overline{M}}$ in (1) the dynamics of the robot manipulator with pneumatic muscles (1) can be rewritten as:

$$\mathbf{\overline{M}\ddot{q} + N(q, \dot{q}, \ddot{q})} = \boldsymbol{\tau} \tag{2}$$

With:

$$\mathbf{N(q, \dot{q}, \ddot{q}) = \left[M(q) - \overline{M}\right]\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + F(q,\dot{q}) + T_d}$$

The design of the NTSMC needs two steps: the choice of sliding surface and the design of the control law. The nonsingular terminal sliding surface for the system (2) can be chosen under its traditional form as following (Amato et al.2013):

$$\mathbf{S = e + \Lambda \dot{e}}^{\boldsymbol{p/q}} \tag{3}$$

Where: $\mathbf{\Lambda = diag(\lambda_{ii})}$ is a diagonal positive matrix, $\boldsymbol{p}$ et $\boldsymbol{q}$ are the positive integer values with $\mathbf{1<}\,\boldsymbol{p/q}\mathbf{<2}$, $\mathbf{e}, \mathbf{\dot{e}}$ are the error vector positions and its derivative.

The derivative of equation (3) and its substituting in equation (2) led us to the control law as:

$$\boldsymbol{\tau} = \mathbf{\overline{M}u + \hat{N}(q,\dot{q},\ddot{q})} \tag{4}$$

Where:

$$\mathbf{u = \ddot{q}_d + \frac{\boldsymbol{q}}{\boldsymbol{p}}\Lambda^{-1}\dot{e}^{2-\boldsymbol{q/p}} + K_{sw}Sgn(S)} \tag{5}$$

And $\mathbf{K}_{\mathbf{sw}}$ is the diagonal matrix with positive elements. $\mathbf{\hat{N}(q,\dot{q},\ddot{q})}$ is obtained using the principal of the Time Delay Estimator method (TDE) (Rezoug et al.2011) such as:

$$\mathbf{\hat{N}(q,\dot{q},\ddot{q}) = N(q,\dot{q},\ddot{q})_{t-L}} \tag{6}$$

$\mathbf{\hat{N}(q,\dot{q},\ddot{q})}$ presents the estimation of $\mathbf{N(q,\dot{q},\ddot{q})}$, $\bullet_{\text{t-L}}$ is the value of $\bullet$ at $\mathbf{t\text{-}L}$, and $\mathbf{L}$ is chosen usually as the sample time. This assumption is applicable only with a sufficiently rapid sampling frequency, which is relative to the studied system. From (4) and (6), we can obtain:

$$\mathbf{N(q,\dot{q},\ddot{q})_{t-L}} = \boldsymbol{\tau}_{\mathbf{t-L}} - \mathbf{\overline{M}\ddot{q}_{t-L}} \tag{7}$$

With the combination of (4) and (7), the terminal sliding mode with time delay estimator can be given as:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{\mathbf{t-L}} - \mathbf{\overline{M}\ddot{q}_{t-L}} + \mathbf{\overline{M}}\left[\mathbf{\ddot{q}_d} + \frac{\boldsymbol{q}}{\boldsymbol{p}}\mathbf{\Lambda^{-1}\dot{e}}^{2-q/p} + \mathbf{K_{sw}Sgn(S)}\right] \tag{8}$$

Stability analysis:

The following candidate Lyapunov function is chosen (Rezoug et al.2011):

$$\mathbf{V = S^T S} \tag{9}$$

The derivation of $\mathbf{V}$ is given as:

$$\begin{aligned}
\mathbf{\dot{V}} &= \mathbf{S^T\dot{S}} \\
&= \mathbf{S^T}\left[\mathbf{\dot{e}} + \frac{\boldsymbol{p}}{\boldsymbol{q}}\mathbf{\Lambda diag}\left(\mathbf{e}^{p/q-1}\right)\mathbf{\ddot{e}}\right] \\
&= \mathbf{S^T}\left\{\mathbf{\dot{e}} + \frac{\boldsymbol{p}}{\boldsymbol{q}}\mathbf{\Lambda diag}\left(\mathbf{e}^{p/q-1}\right)\right. \\
&\quad \left.\times\left[-\frac{\boldsymbol{p}}{\boldsymbol{q}}\mathbf{\Lambda^{-1}\dot{e}}^{2-q/p} - \mathbf{K_{sw}sign(S)} + \boldsymbol{\varepsilon}\right]\right\}
\end{aligned}$$

Then $\mathbf{\dot{V}}$ is given as:

$$\mathbf{\dot{V}} = \mathbf{S^T}\left[\frac{\boldsymbol{p}}{\boldsymbol{q}}\mathbf{\Lambda^{-1}\dot{e}}^{q/p-1}\left(-\mathbf{K_{sw}sign(S)} + \boldsymbol{\varepsilon}\right)\right] \tag{10}$$

With the TDE error ε is written as:

$$\varepsilon \overset{\Delta}{=} \overline{\mathbf{M}}^{-1}(\mathbf{N} - \mathbf{N}_{t-T}) \quad (11)$$

In equation (10), $\dot{\mathbf{e}}^{q/p-1}$ is defined positive for $\dot{\mathbf{e}}_i \neq 0$ (V.I. Utkin, and K.D. Young 1978), if we choose $\{\mathbf{K}_{sw}\}_{ii} > \varepsilon_i \;\; i=1\ldots n$. The time derivative of the Lyapunov function (10) is negative definite as:

$$\dot{\mathbf{V}} = \mathbf{S}^T\left[\frac{p}{q}\Lambda^{-1}\dot{\mathbf{e}}^{q/p-1}\left(-\mathbf{K}_{sw}\mathbf{sign}(\mathbf{S})+\varepsilon\right)\right] \leq 0 \quad (12)$$

3. EXPERIMENTAL STUDY OF THE NTSM CONTROLLER TO THE ROBOT MANIPULATOR WITH PAMS

3.1 Robot description

In order to make in evidence the proposed approach, experimentations have been realized using 7-degree of freedom robot depicted in Figure 1. This robot manipulator and its PAMs by which it is driven are both manufactured at the INSA robotic laboratory of Toulouse (France). The kinematic and mechanical structures of the robot have been described elsewhere in (Tondu et al.2005). We have chosen this robot for its suitability for domestic application. In the reported experiments, we restricted our control work to the two shoulder and elbow flexion-extension movements. This choice was motivated by the fact that separated and combined movements of these joints make possible to highlight the performances of the controller face to the typical serial chain robotics non-linearity and, particularly, to these induced by the artificial muscle actuation mode. We give in Table 1 the joint ranges and main dynamic parameters for the two considered links and the inertial variations generated by this additional load.

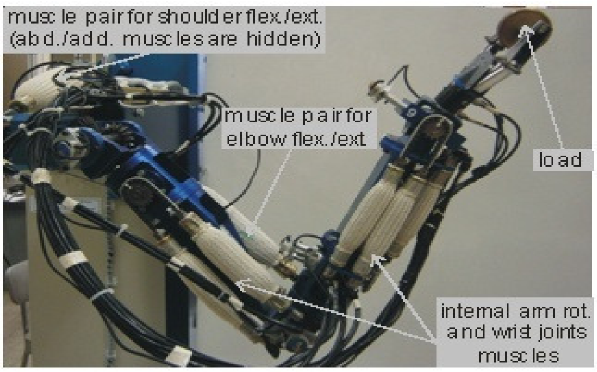


Fig. 1. INSA of Toulouse 7-DOF robot arm actuated by PAMs.

The actuator singularities are linked to the non-linear dynamic behaviour of the artificial muscle itself, particularly due to inherent complex friction phenomena. The intensity-pressure converter feeding in air every artificial muscle and associated tubing are another source of actuator non-linearities due to the fact that the artificial muscle volume increases during contraction. As a consequence, the dynamic response of the artificial muscle directly depends on the muscle size (K. Braikia et al. 2011).

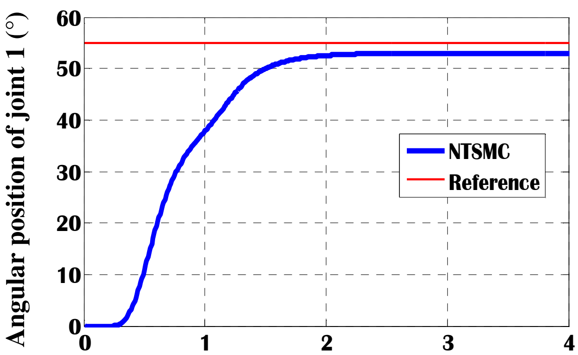
Table 1. Shoulder and elbow flexion-extension kinematic and dynamic data.

	Joint range (deg)	Peak torque (N.m)	Maximum inertia ($kg.m^2$)	Maximum inertia variation with additional load
Shoulder flexion-extension	[0-180°]	67	0.9	12 %
Elbow flexion-extension	[0-150°]	25	0.11	24 %

3.2 Experimental results

3.2.1 Regulation mode

The regulation mode is considerate in the experimentations. The joint one and two moves one steps with $\mathbf{q_{d1}=55°}$ and $\mathbf{q_{d2}= 100°}$, respectively. In order to avoid the chattering drawback classical NTSMC is applied with the saturation function. The use of saturation function with relative thin boundary layer maintains the stability and the robustness in closed loop of the controlled robot. Joint one and two were experimented sufficient time equal to 4 second. The sampling time is 10ms. We have chosen to present the angular position, the control signals and the evolution of the sliding surfaces. The used experimental parameters are: For joint 1 we have the following values: q=3, p=5, $\overline{\mathbf{M}}_{11} = \mathbf{0.25}$, $\mathbf{\Phi}_{11} = \mathbf{1}$ and $\lambda_{11} = \mathbf{20}$. For joint 2 we have the following values: q=3, p=5, $\overline{\mathbf{M}}_{22} = \mathbf{94}$, $\mathbf{\Phi}_{22} = \mathbf{1}$ and $\lambda_{22} = \mathbf{12}$. Figures 2 and 3 present the experimental results in regulation mode for joint 1 and 2, respectively. It is interest to say that the **M** matrix parameters' are obtained experimentally through the test and error method.



(a)

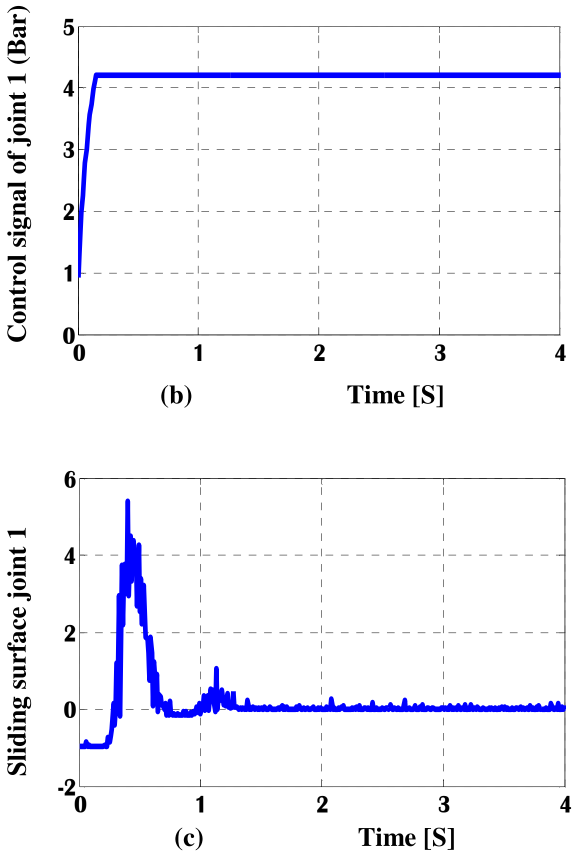
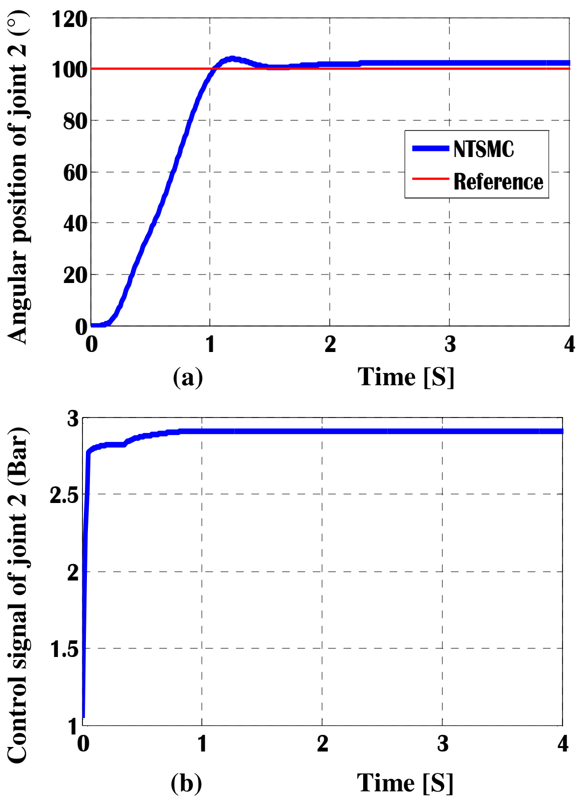


Fig. 2 Experimental results of the NTSMC for joint 1 (a) Position response (b) Control signal (c) Sliding surface.



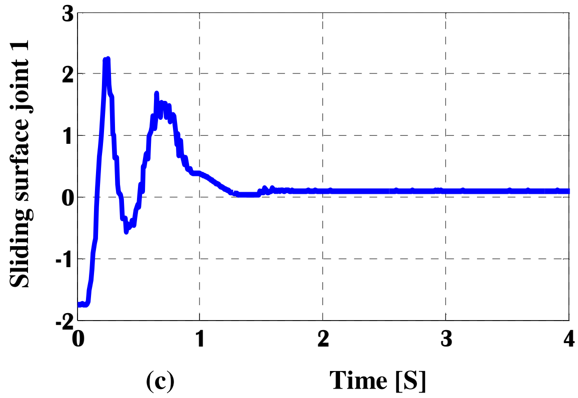


Fig. 3 Experimental results of the NTSMC for joint 2 (a) Position response (b) Control signal (c) Sliding surface.

3.2.2 Trajectory tracking mode

In order to examine the ability of the previous presented control approach to make joint 2 track sinusoidal trajectory, this section is adopted. Hence, the joint 2 is initially at (q_2=0◦), it is commanded to follow a desired trajectory **q_{d2}(t)=50.sin(2.pi.f.t)+50,** with frequency **f=0.3ms.** The experimentation results are shown in Figure 4. In trajectory tracking mode, we choose to present the position responses and the control signals. The parameters of the TDE-based NTSMC are selected as: $p = 5$, $q = 3$, $\bar{M}_{22} = 0.005$ and $\lambda_{22} = 17.4$ $\Phi_{22} = 1$.

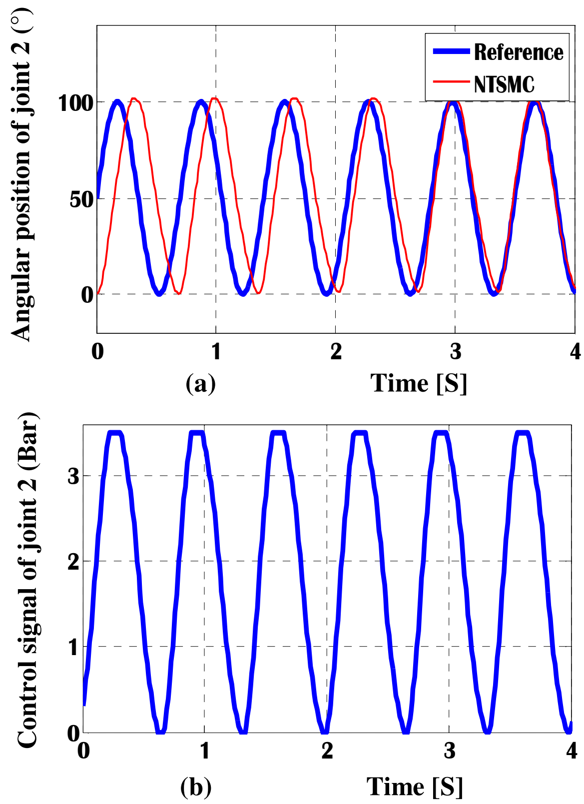


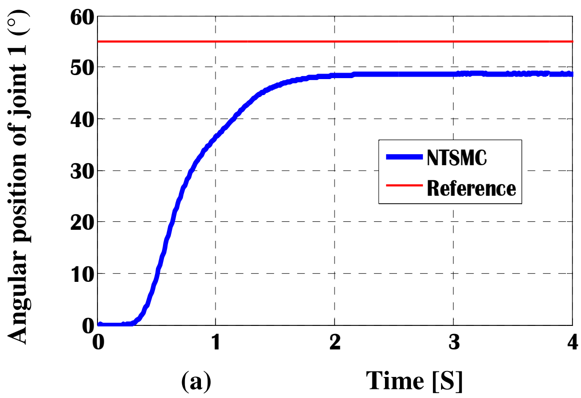
Fig. 4 Experimental results of joint 2 (a) Position response (b) Control signal (c) Sliding surface.

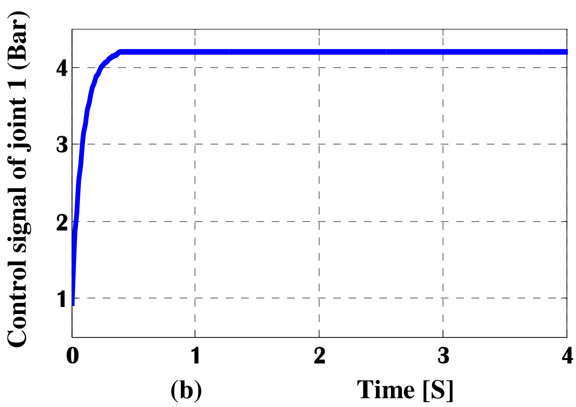
In regulation mode, from the experimental results, it can be seen that the NTSMC can achieve best control performance, reporting to the angular position response.

In trajectory tracking mode we use only the joint 2 because of the strong nonlinearity of joint1. The chosen action is greatly sped for this reason joint 2 arrives to flow the desirable trajectory only after 2s, after that the joint displacement is harmonious and error is very little. The control signals are same in the all cases.

3.2.3 Robustness tests

In order to test the ability of the controller to keep robust when some external load is applied. We have also considered the case of an additional load of m=0.235 kg placed at the grip center as shown in Figure 1. In this experience, we maintain the same desirable angles 55° for joint 1 and 100° for joint 2, hence the experimental parameters are also same. As in the above regulation case figures (4) and (6) present the results in angular position, the applied control and the sliding surfaces for the regulation mode for all joints. The angular position and the control signal are show in the case of trajectory tracking mode for joint 2 (figure 7). The references in all cases are given by red lines and the experimental results in bleu lines. Experimental tests are effectuated during 4 S for a sample time of 10ms.





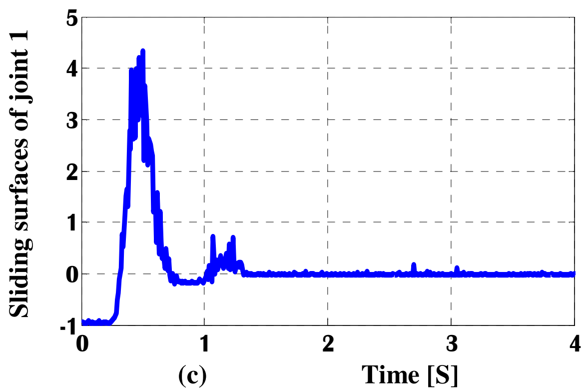
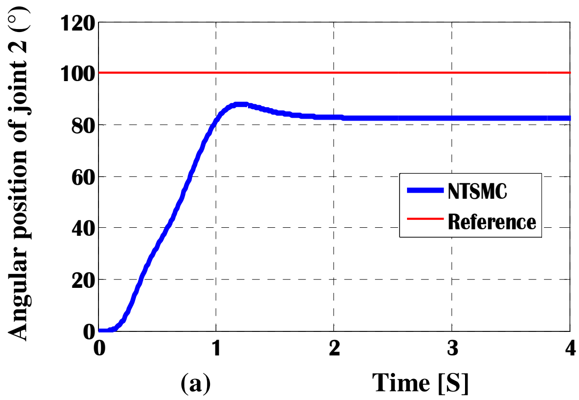
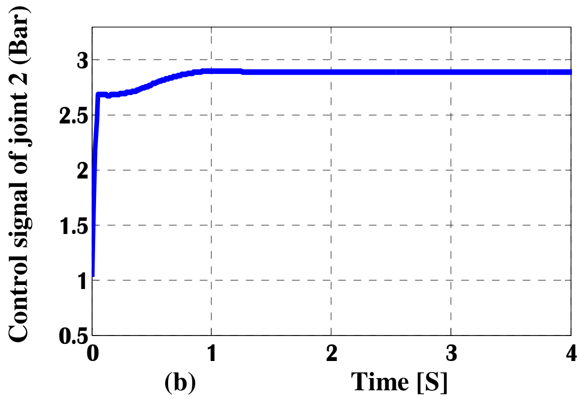


Fig.5. Robustness tests of joint 1 (a) Position response (b) Control signal (c) Sliding surface.





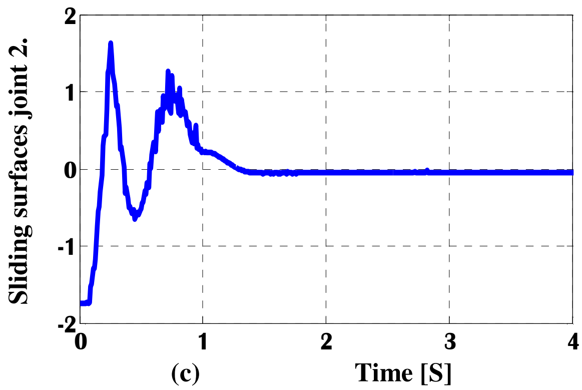


Fig.6. Robustness tests of joint 2 (a) Position response (b) Control signal (c) Sliding surface.

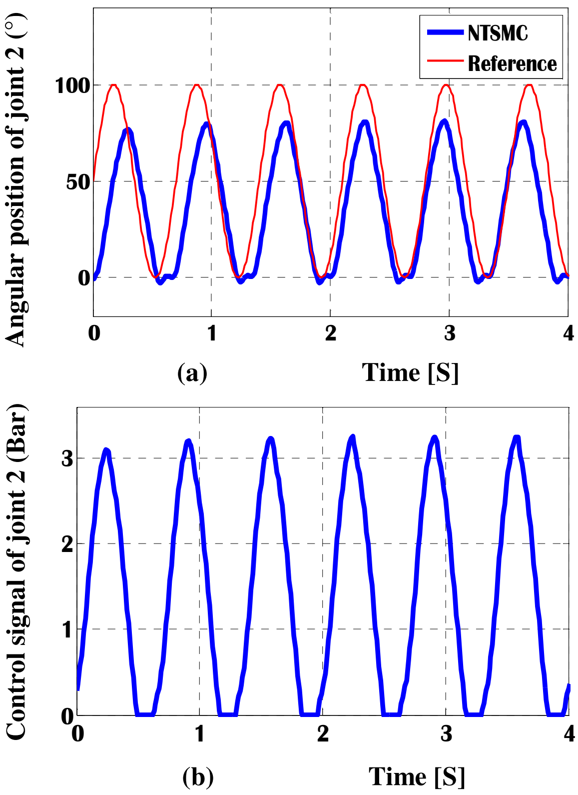


Fig.7. Robustness tests of joint 2 (a) Position response (b) Control signal.

From point of view of robustness the terminal sliding mode control has been relatively able to overcome the errors induced by the mass uncertainty seeing figures 6 and 7. The static errors appeared essentially in regulation mode are produced by the friction, the gravitational forces, the non-linear dynamic behavior of the artificial muscle and the coupling between the joints.

4. CONCLUSION

Robust control approach called nonsingular terminal sliding mode has been experimented under robotic manipulator actuated by PAMs. The nonsingular terminal sliding mode with time delay estimator is used for avoiding the modeling of the used PAMs robot manipulator. In order to attenuate the chattering effect we have replaced the hitting control by saturation function. The fusibility, the effectiveness and the robustness of the proposed approach have been proved through experimental results in regulation and in trajectory tracking modes. Future works will be focused around the making of a robust observer for estimating of the terminal sliding surfaces.

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