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RESEARCH ARTICLE

ADAPTIVE FUZZY STATE OBSERVER BASED ROBUST CONTROLLER FOR A ROBOTIC SYSTEM

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Abstract

In this paper we propose to develop an adaptive type-2 fuzzy robust controller with a stat observer to control a robotic system. For this, we the approximate the system with two type-2 fuzzy systems. To overcome the problem of the state measures, we propose a state observer allowing to converge quickly to the real values and hence guarantees the stability of the closed loop system. The robustness of the closed loop system is ensured by using a modified sliding mode control, where the chattering phenomenon are removed. Simulation results are given to show the efficiency of the proposed approach.

Introduction:-

Fuzzy logic has been widely used in several applications because it can be considered as very good model-free approach, for modelling and controlling imprecisely defined and uncrtain systems[1]–[3]. A fuzzy controller is synthesized from a collection of fuzzy If–Then rules; i.e., constructed from human expertise. In the case of luck of information, we can update the conclusion part according to adaptation laws deduced from the stability analysis. This may be insufficient in presence of uncertainties. Type-2 fuzzy logic has been developed to resolve these problems because they use fuzzy values and not ones which allow to take in account uncertainties [4]-[5].

Siding mode control is one of most used robust control laws due their simplicity and robustness [6]. However, classical sliding mode control suffers from some difficulties. First, the discontinuity in the control action becomes the cause of chattering, which is undesirable in most applications [7]. In practical implementations, the chattering may cause an unnecessarily large control signal as the system uncertainties are large and may damage system components such as actuators. To solve this problem, several solutions have been developed in the literature [8]. However, in these works we should ensure a trad off between the tracking performancesand chattering elimination.

In this work, we propose use two type-2 adaptive fuzzy systems to approximate the system dynamics. The control law is based on sling mode control. To eliminate the chattering phenomena an adaptive fuzzy system is used for approaching phase. To ensure a quick convergence of the adaptive algorithm, we use a PID control law. Furthermore, we have added a control term reduce the effect of external disturbances and approximation errors. Although, to overcome the availability of state variables for measurement, we have added a state observer. This later has been constructed such that the convergence to the real value in a small time. The closed loop stability and the convergence of the adaptation laws are studied using Lyapunov theory. To illustrate the performances of the proposed approach, simulations are presented.

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The paper is organized as follows: section 2 is dedicated to the problem statement. Section 3 introduces type-2 fuzzy systems and the design of the proposed control law. Simulation and results are given section 4. Conclusion and perspectives are given in section 5.

Problem statement:-

Let us consider the dynamic equation of n degree-of-freedom robotic manipulators as follows

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q,\dot{q}) = \Gamma(t) + \Gamma_{ext}(t) \qquad (1)$$

where q, $\dot{q}$ and $\ddot{q} \in \mathbb{R}^n$ are the vector of joint position, joint velocity, and joint acceleration, respectively. $M(q) \in \mathbb{R}^{n\times n}$ is a symmetric and positive definite inertia matrix, $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$ is the matrix of centrifugal and Coriolis forces, $G(q) \in \mathbb{R}^n$ is the vector of gravitational forces, $\Gamma(t) \in \mathbb{R}^n$ is the vector of input joint torque and $\Gamma_{ext}(t) \in \mathbb{R}^n$ is the vector of unknown external disturbances. Equation (1) can be rewritten in a compact form as follows:

$$\ddot{q} = -M^{-1}(q)[C(q,\dot{q})\dot{q} + G(q,\dot{q})] + M^{-1}(q)\Gamma(t) + M^{-1}\Gamma_{ext}(t) \qquad (2)$$

$$\ddot{q} = f(q,\dot{q}) + g(q,\dot{q})\Gamma(t) + d(t) \qquad (3)$$

Where:

$$f(q,\dot{q}) = -M^{-1}(q)[C(q,\dot{q})\dot{q} + G(q,\dot{q})]$$

$$g(q,\dot{q}) = M^{-1}(q)\Gamma(t)$$

$$d(t) = M^{-1}\Gamma_{ext}(t).$$

For practical applications, it is difficult if not impossible to know the exact dynamic model of the robotic manipulators. Hence, we propose to approximate them with two type-2 adaptive fuzzy systems. The robustness of the close d loop system can be guaranteed by sliding mode control.

Control Design:-

Interval Type-2 fuzzy logic system

Fuzzy Logic Systems are known as the universal approximators and have several applications in control design and identification. A type-1 fuzzy system consists of four major parts: fuzzifier, rule base, inference engine, and defuzzifier. A T2FLS is very similar to a T1FLS [9], the major structure difference being that the defuzzifier block of a type-1 fuzzy system is replaced by the output processing block in a type-2 fuzzy system, which consists of type-reduction followed by defuzzification [9]–[12].

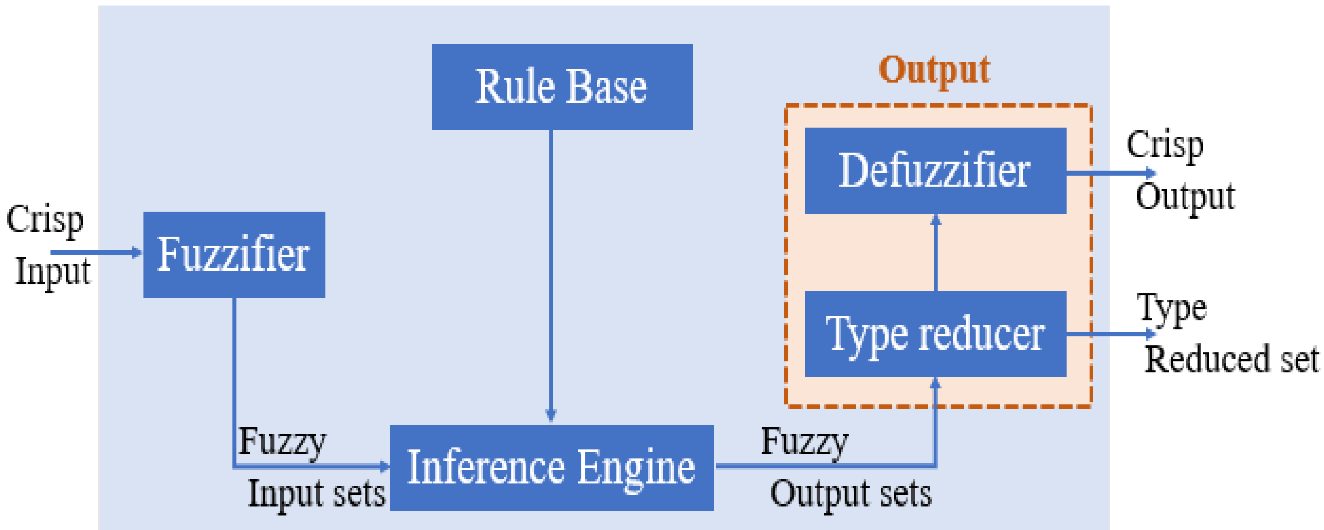

Figure 1:- Structure of a type-2 fuzzy logic system.

In a interval type-2 fuzzy system, a triangular fuzzy set is defined by a lower and upper set as shown in figure 2.

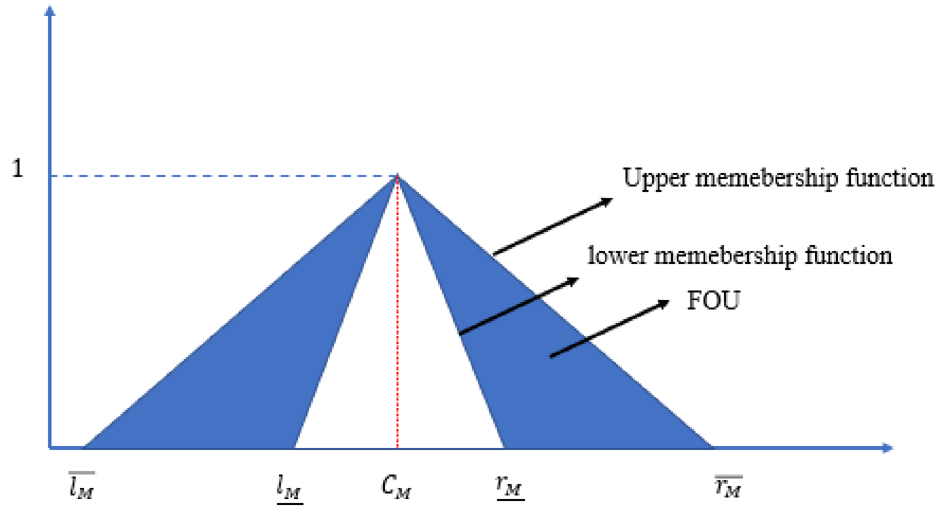

Figure 2:- Interval type-2 triangular fuzzy sets.

It is clear that the interval type-2 fuzzy set is in a region bounded by an upper membership function and a lower membership function denoted as $\bar{\mu}_{\tilde{A}(x)}$ and $\underline{\mu}_{\tilde{A}}$ respectively and is named a foot of uncertainty (FOU). Assume that there are M rules in a type-2 fuzzy rule base, each of them has the following form:

$$R^i: \quad IF x_1 is \tilde{F}_1^i and \ldots and x_n is \tilde{F}_n^i THEN y is [w_l^i w_r^i]$$

Where $x_j j = 1,2, \ldots, n$ and y are the input and output variables of variables of the type 2 fuzzy system, respectively, the $\tilde{F}_j^i$ is the type 2 fuzzy sets of antecedent part, and $[w_l^i w_r^i]$ is the weighting interval set in the consequent part. The operation of type-reduction is to give a type-1 set from a type-2 set. In the meantime, the firing strength Fi for the i^{th} rule can be an interval type-2 set expressed as:

$$F^i \equiv \left[\underline{f}^i, \bar{f}^i\right]$$

Where

$$\begin{cases} \underline{f}^i = \underline{\mu}_{\tilde{F}_1^i}(x_1) * \ldots * \underline{\mu}_{\tilde{F}_n^i}(x_n) \\ \bar{f}^i = \bar{\mu}_{\tilde{F}_1^i}(x_1) * \ldots * \bar{\mu}_{\tilde{F}_1^i}(x_n) \end{cases}$$

In this work, the center of set type-reduction method is used to simplify the notation. Therefore, the output can be expressed as:

$$y_{cos}(x) = [y_l ; y_r]$$

Where $y_{cos}(x)$ is also an interval type 1 set determined by left and right most points (y_l and y_r), witch can be derived from consequent centroid set $[w_l^i w_r^i]$ (either $\underline{w}^i$ or $\bar{w}^i$) and the firing strength $f^i \in F^i \equiv \left[\underline{f}^i, \bar{f}^i\right]$. The interval set $[w_l^i w_r^i]$ $(i = 1, \ldots, M)$ should be computed or set first before the computation of $y_{cos}(x)$. Hence, left most point y_l and right most point y_r can be expressed as:

$$\begin{cases} y_l = \frac{\sum_{i=1}^{M} \underline{f}^i w_l^i}{\sum_{i=1}^{M} \underline{f}^i} \\ y_r = \frac{\sum_{i=1}^{M} \bar{f}^i w_r^i}{\sum_{i=1}^{M} \bar{f}^i} \end{cases} \quad (4)$$

Using the center of set type reduction method to compute y_l and y_r the defuzzified crisp output from an interval type 2 fuzzy logic system can be obtained according to the following equation:

$$y(x) = \frac{y_l + y_r}{2} \quad (5)$$

Which can be rewritten on the following vectorial form:

$$y(x) = \Psi^T(x).w \quad (6)$$

Where $\Psi^T(x)$ represents the regressive vector and w the consequent vector containing the conclusion values of the fuzzy rules.

Then, we can define the approximators of $f(q,\dot{q})$ and $g(q,\dot{q})$ as follows:

$$\begin{cases} \hat{f}(q,\dot{q}) = \Psi_f^T(x).w_f \\ \hat{g}(q,\dot{q}) = \Psi_g^T(x).w_g \end{cases} \quad (7)$$

We can also define the minimal approximation errors by $\delta_{min}^f = f(q,\dot{q}) - \hat{f}^*(q,\dot{q})$ and $\delta_{min}^g = g(q,\dot{q}) - \hat{g}^*(q,\dot{q})$ Where: $\hat{f}^*(q,\dot{q}) = \Psi_f^T(x).w_f^*$ and $\hat{g}^*(q,\dot{q}) = \Psi_g^T(x).w_g^*$ represent the optimal values of $\hat{f}(q,\dot{q})$ and $\hat{g}(q,\dot{q})$ respectively, and the approximation errors as $\delta_f = f(q,\dot{q}) - \hat{f}(q,\dot{q})$ and $\delta_g = g(q,\dot{q}) - \hat{g}^*(q,\dot{q})$.

Control Law Synthesis

Using equation (7), our robotic system of (3) can be described by the new expression:

$$\ddot{q} = \hat{f}(q,\dot{q}) + \hat{g}(q,\dot{q})\Gamma(t) + \Psi_f^T(x).\widetilde{w}_f + \Psi_g^T(x).\widetilde{w}_g\Gamma(t) + d_e(t) \quad (8)$$

Where $d_e(t)$ regroups external disturbances and approximation errors. It should be noted that this term always remains bounded. $\widetilde{w}_i = w_i^* - w_i; i = f,g$.

Rewriting the above equation on a vectorial form gives:

$$\begin{cases} \dot{\underline{q}} & = A_0\underline{q} + B\begin{bmatrix} \hat{f}\left(\underline{q}\right) + \Psi_f^T\left(\underline{q}\right).\widetilde{w}_f + \hat{g}\left(\underline{q}\right)\Gamma(t) \\ +\Psi_g^T\left(\underline{q}\right).\widetilde{w}_g\Gamma(t) + d_e(t) \end{bmatrix} \\ q & = C^T\underline{q} \end{cases} \quad (9)$$

Where:

$A_0 = \begin{bmatrix} 0 & I \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ I \end{bmatrix}$, $C = \begin{bmatrix} I \\ 0 \end{bmatrix}$ and $\underline{q} = \begin{bmatrix} q \\ \dot{q} \end{bmatrix}$

Using the observed states $\hat{\underline{q}} = \begin{bmatrix} \hat{q} \\ \hat{\dot{q}} \end{bmatrix}$, our control law can be written as follows:

$$\Gamma(t) = \hat{g}^{-1}\left(\hat{\underline{q}}\right)\left[-\hat{f}\left(\hat{\underline{q}}\right) + \ddot{q}_{ref} + k^T\hat{\underline{e}} - u_a - \frac{\hat{S}}{\rho^2}\right] \quad (10)$$

Where u_a is an adaptive type-2 fuzzy system introduced to eliminate at best the approximation errors and the external disturbances, and the term $\frac{\hat{S}}{\rho^2}$ is introduced to attenuate the effect of the residual errors to a prescribed level ρ. $\hat{\underline{e}} = \left[q_{ref} - \hat{q}, \dot{q}_{ref} - \hat{\dot{q}}\right]$ represents the estimation of the tracking error [13]-[15].

Using (10), we can obtain:

$$\begin{cases} \dot{\underline{q}} & = A_0\underline{q} + B\begin{bmatrix} \ddot{q}_{ref} + k^T\hat{\underline{e}} - u_a - \frac{\hat{S}}{\rho^2} + \Psi_f^T\left(\underline{q}\right).\widetilde{w}_f \\ +\hat{g}\left(\underline{q}\right)\Gamma(t) + \Psi_g^T\left(\underline{q}\right).\widetilde{w}_g\Gamma(t) + d_e(t) \end{bmatrix} \\ q & = C^T\underline{q} \end{cases} \quad (11)$$

Therefore, the equation of the dynamic error can be written as:

$$\begin{cases} \dot{\underline{e}} & = A_0\underline{e} - B\begin{bmatrix} k^T\hat{\underline{e}} - u_a - \frac{\hat{S}}{\rho^2} + \Psi_f^T\left(\underline{q}\right).\widetilde{w}_f \\ +\hat{g}\left(\underline{q}\right)\Gamma(t) + \Psi_g^T\left(\underline{q}\right).\widetilde{w}_g\Gamma(t) + d_e(t) \end{bmatrix} \\ e & = C^T\underline{e} \end{cases} \quad (12)$$

To construct the state observer, we consider:

$$\dot{\hat{\underline{q}}} = A_0\hat{\underline{q}} + B\left[\ddot{q}_{ref} + k^T\hat{\underline{e}} - u_o - \frac{\hat{S}}{\rho^2}\right] - L(q - \hat{q}) \quad (13)$$

Where the term u_o is introduced to compensate the estimation error. Hence the estimation of the tracking error can be given on the vectorial form by:

$$\dot{\tilde{\underline{e}}} = A\tilde{\underline{e}} + B\left[u_a - \Psi_f^T\left(\hat{\underline{q}}\right).\widetilde{w}_f - \Psi_g^T\left(\hat{\underline{q}}\right).\widetilde{w}_g\Gamma(t) - d_e(t) - u_o\right] \quad (14)$$

With $A = A_0 - LC^T$.

Our next task is to deduce the adaptation laws and the expression of the signal u_o allowing to respect the constraints related to the stability. Let define the error $e_s = \hat{q} - q$ whose the expression is given by the following equation:

$$e_s = C^T[sI - A]^{-1}B\left[u_a - \Psi_f^T\left(\underline{\hat{q}}\right).\tilde{w}_f - \Psi_g^T\left(\underline{\hat{q}}\right).\tilde{w}_g\Gamma(t) - d_e(t) - u_o\right] \quad (14)$$

Where s denotes the differential Laplace operator.

Let H(s) the transfer function defined by

$$H^{-1}(s) = C^T[sI - A]^{-1}B \quad (15)$$

Based on Meyer-Kalman-Yokubovic Lemma, we can introduce a stable transfer function $T(s)$such that $T(s).H^{-1}(s)$will be strictly positive real.

Then we can obtain:

$$\dot{\underline{e}} = A\underline{e} + B_1\left[u_a^s - \Psi_f^{sT}\left(\underline{\hat{q}}\right).\tilde{w}_f - \Psi_g^{sT}\left(\underline{\hat{q}}\right).\tilde{w}_g\Gamma(t) - d_e^s(t) - u_o^s\right] \quad (16)$$

Where:

$$u_a^s = T^{-1}(s).u_a$$
$$\Psi_f^{sT}\left(\underline{\hat{q}}\right) = T^{-1}(s).\Psi_f^T\left(\underline{\hat{q}}\right)$$
$$\Psi_g^{sT}\left(\underline{\hat{q}}\right) = T^{-1}(s).\Psi_g^T\left(\underline{\hat{q}}\right)$$
$$d_e^s(t) = T^{-1}(s).d_e(t)$$
$$u_o^s = T^{-1}(s).u_o$$

According to Meyer-Kalman-Yokubovic Lemma, there exists a positive definite symmetric matrix P such that [13], [16]-[17]:

$$A^T.P + PA = -Q; PB_1 = C \quad (17)$$

Where Q is a positive definite symmetric matrix. The adaptive algorithm of $u_a^s = \psi^s\left(\underline{\hat{q}}\right)\Theta$, we use a PID law given as follows:

$$\begin{aligned}\theta &= -\gamma_1\left[\psi^s\left(\underline{\hat{q}}\right)\right]^{-1}C^T\underline{\tilde{e}} - \gamma_2\int_0^t\left[\psi^s\left(\underline{\hat{q}}\right)\right]^{-1}C^T\underline{\tilde{e}}.dt \\ &-\gamma_1\frac{d}{dt}\left[\psi^s\left(\underline{\hat{q}}\right)\right]^{-1}C^T\underline{\tilde{e}} \\ &= -\gamma_1\chi_1 - \gamma_2\chi_2 - \gamma_1\chi_3\end{aligned} \quad (18)$$

Where γ_1 and γ_2 are two positive constants.

To study the global stability of the closed loop system and to give the expression of the signal u_o^s, we choose the following Lyapunov function:

$$V = \frac{1}{2}\underline{\tilde{e}}^TP\underline{\tilde{e}} + \frac{1}{2\eta_f}\tilde{w}_f^T.\tilde{w}_f + \frac{1}{2\eta_g}\tilde{w}_g^T.\tilde{w}_g + \gamma_1\chi_1^T.\chi_1 - \gamma_2\chi_2^T.\chi_2 \quad (19)$$

Using (16), (17) and (18), and the relation between the terms $\chi_i(i = 1,2,3)$ the time derivative of above equation can be written as:

$$\begin{aligned}\dot{V} \leq\; & -\underline{\tilde{e}}^TQ\underline{\tilde{e}} + \underline{\tilde{e}}^TC[-d_e^s(t) - u_o^s] \\ & -\frac{1}{\eta_f}\tilde{w}_f^T.\left[\dot{w}_f + \eta_f\Psi_f^s\left(\underline{\hat{q}}\right)\right] \\ & -\frac{1}{\eta_g}\tilde{w}_g^T.\left[\dot{w}_g + \eta_g\Psi_g^s\left(\underline{\hat{q}}\right)\Gamma(t)\right]\end{aligned} \quad (20)$$

If we choose the adaptation laws and the control signal as:

$$\begin{cases}\dot{w}_f = -\eta_f\Psi_f^s\left(\underline{\hat{q}}\right) \\ \dot{w}_g - \eta_g\Psi_g^s\left(\underline{\hat{q}}\right)\Gamma(t) \\ u_o^s = \frac{1}{2\sigma^2}C^T\underline{\tilde{e}}\end{cases} \quad (21)$$

The inequality (20) becomes:

$$\begin{aligned}\dot{V} &\leq -\underline{\tilde{e}}^TQ\underline{\tilde{e}} - \underline{\tilde{e}}^TC[d_e^s(t)] - \frac{1}{2\sigma^2}\underline{\tilde{e}}^TCC^T\underline{\tilde{e}} \\ &\leq -\underline{\tilde{e}}^TQ\underline{\tilde{e}} + \sigma^2[d_e^s(t)]^2\end{aligned} \quad (22)$$

Integrating this inequality leads to

$$\int_0^t\underline{\tilde{e}}^TQ\underline{\tilde{e}}.d\tau \leq V(0) + \sigma^2\int_0^t[d_e^s(t)].d\tau \quad (23)$$

This inequality can be considered as the H∞ criterion guaranteeing the global stability of the closed loop system.

Results and Discussion:-

To illustrate the effectiveness of the proposed controller, we consider a two-link robot described by:

$$\begin{bmatrix} M_{11}(q) & M_{12}(q) \\ M_{21}(q) & M_{22}(q) \end{bmatrix} \begin{bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \end{bmatrix} + \begin{bmatrix} C_{11}(q,\dot{q}) & C_{12}(q,\dot{q}) \\ C_{21}(q,\dot{q}) & C_{22}(q,\dot{q}) \end{bmatrix} \begin{bmatrix} \dot{q}_1 \\ \dot{q}_2 \end{bmatrix} + \begin{bmatrix} G_1(q) \\ G_2(q) \end{bmatrix} = \begin{bmatrix} \Gamma_1(t) \\ \Gamma_2(t) \end{bmatrix} + \begin{bmatrix} \Gamma_{ext\,1}(t) \\ \Gamma_{ext\,2}(t) \end{bmatrix}$$

Where:

$$M_{11}(q) = (m_1 + m_2)l_1^2$$
$$M_{12}(q) = M_{21}(q) = m_2 l_1 l_2 (\sin(q_1)\sin(q_2) + \cos(q_1)\cos(q_2))$$
$$M_{22}(q) = m_2 l_2^2$$
$$C_{11}(q,\dot{q}) = -m_2 l_1 l_2 (\cos(q_1)\sin(q_2) - \sin(q_1)\cos(q_2))\dot{q}_2$$
$$C_{21}(q,\dot{q}) = -m_2 l_1 l_2 (\cos(q_1)\sin(q_2) - \sin(q_1)\cos(q_2))\dot{q}_1$$
$$C_{11}(q,\dot{q}) = C_{22}(q,\dot{q}) = 0$$
$$G_1(q) = -(m_1 + m_2) l_1 g.\sin(q_1)$$
$$G_2(q) = -m_2 l_2 g.\sin(q_2)$$
$$m_1 = m_2 = 1Kg; l_1 = l_2 = 1m; g = 9.8ms^{-2}$$

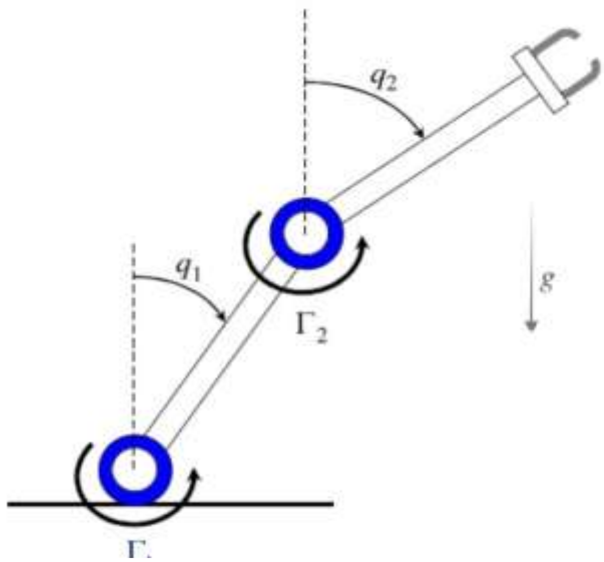

Figure 3:- Considered two links robot.

To construct the type 2 fuzzy nominal model, we consider that the positions q_1 and q_2 are constrained within $\left[-\frac{\pi}{2};\frac{\pi}{2}\right]$, which leads to nine fuzzy rules. Each one of them gives the relation between the equilibrium point and the corresponding local model. For simulation we consider a reference trajectory in the form :$q_{ref} = \sin(t)$. For the other parameters:

$$k = \begin{bmatrix} 2 & 1 \\ 2 & 1 \end{bmatrix}, L = \begin{bmatrix} 44 & 44 \\ 44 & 44 \end{bmatrix}, T(p) = \begin{bmatrix} s+2 \\ s+2 \end{bmatrix}, \eta_f = 150, \eta_g = 0.1, \gamma_1 = 10; \gamma_2 = 0.1.$$

The simulation results for a sinusoidal reference trajectory using the proposed approach are given in Figures 4 to 6. The state trajectories and their reference signals are depicted in Figure 4. The convergence of the estimation errors is shown in Figure 5. The applied control signals are given in Figure .6. We remark the convergence of the system to the reference trajectories and the control signal doesn't contain any abrupt variations or chattering. Also, we remark the good convergence of the observed values to their real one, which confirms the performances of the proposed approach.

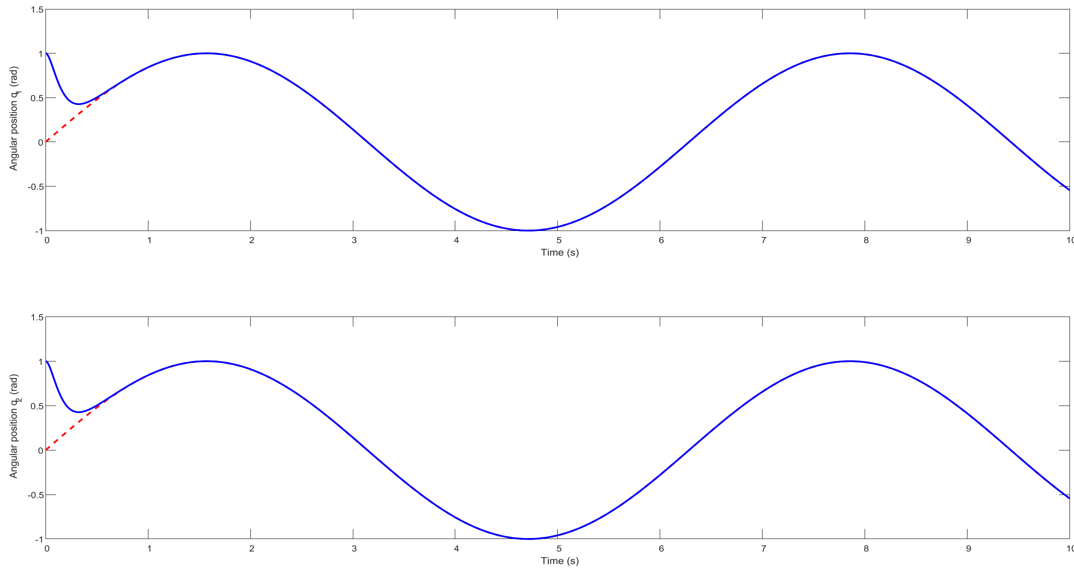

Figure 4:- Position and their reference signals.

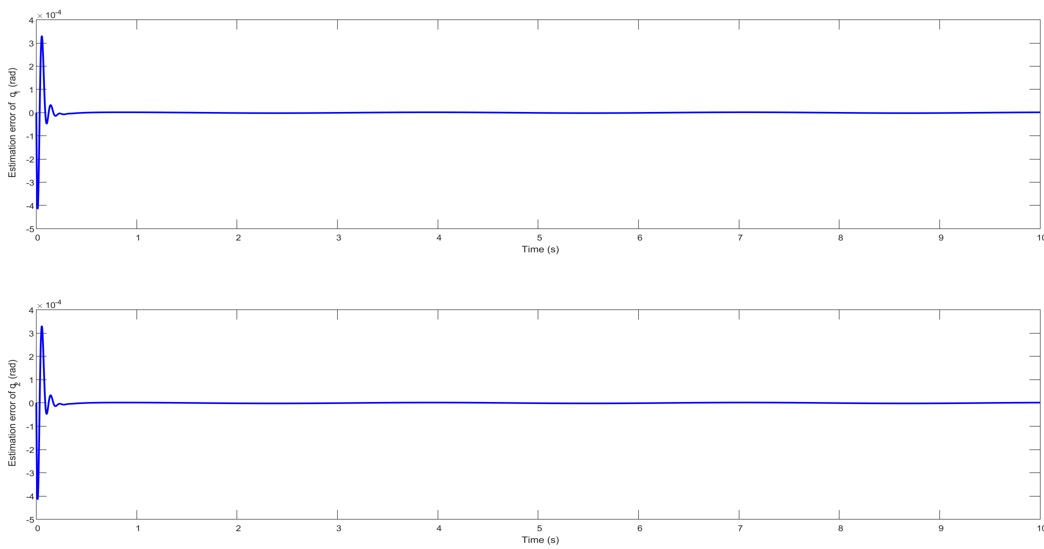

Figure 5:- Errors of Angular position.

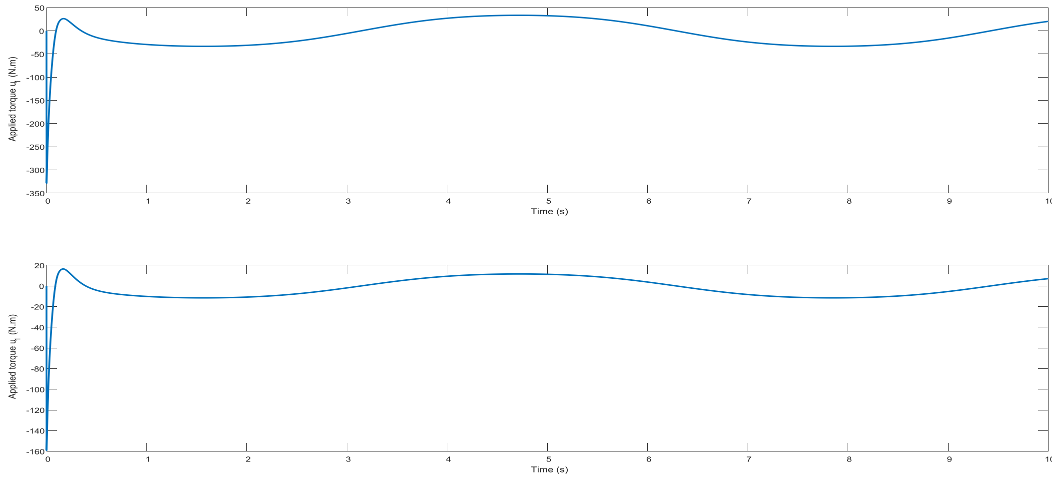

Figure 6:- Applied torques for each link.

Conclusions:-

In this work a robust sling mode controller based on type-2 fuzzy logic and state observer for a robotic system has been presented. Indeed, suing type-2 adaptive fuzzy systems allows to obtain a good approximation of the system without a good knowledge. Furthermore, the use of the state observer allows to reduce the used sensors and hence the implementation cost. Simulation results illustrate the objectives of this paper. As perspective of this work, a real time implementation of this approach.

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