Design dual-fuzzy adaptive controller based on method backstepping for industrial robotic manipulators

Thiết kế bộ điều khiển thích nghi mờ kép dựa trên phương pháp cuốn chiếu cho tay máy robot công nghiệp

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Abstract

In this study, a combination of multi-input fuzzy control, single-input fuzzy control, sliding mode control and backstepping control is introduced to the industrial robot manipulator (IRM). Simulation results show the high performance of this control method when compared to adouble-fuzzy backstepping sliding mode controller (DFBSMC) and Fuzzy Backstepping Sliding Mode Controller controller (FBSMC). Moreover, the effectiveness of the controller is also demonstrated through simulation and experiment results when comparing the proposed controller with FBSMC and DFBSMC. The simulation results show that the convergence speed, braking ability, grip error, stability, fast response, overshoot of the proposed controller DFBSMC are better than the FBSMC controller. Thereby concluding, the suggested control is accordance for adaptive-robust-fuzzy double controller and can be used as supplement and replace of traditional backstepping control.

Key Words: *Industrial robot manipulator; robust adaptive fuzzy double control; sliding control, backstepping control.*

Tóm tắt

Trong nghiên cứu này, sự kết hợp của điều khiển mờ nhiều đầu vào, điều khiển mờ một đầu vào, điều khiển chế độ trượt và điều khiển backsteping được giới thiệu cho điều khiển tay máy robot công nghiệp (IRM). Kết quả mô phỏng cho thấy hiệu suất cao của phương pháp điều khiển này khi so sánh với bộ điều khiển chế độ trượt backsteping mờ kép bám thích nghi (DFBSMC) và bộ điều khiển chế độ trượt backstepping mờ (DFBSMC)). Hơn nữa, tính hiệu quả của bộ điều khiển còn được chứng minh qua các kết quả mô phỏng và thí nghiệm khi so sánh bộ điều khiển được đề xuất với FBSMC và DFBSMC. Kết quả mô phỏng cho thấy tốc độ hội tụ, khả năng phanh, sai số bám, độ ổn định, phản ứng nhanh, vọt lố của bộ điều khiển đề xuất DFBSMC tốt hơn bộ điều khiển FBSMC. Qua đó kết luận, điều khiển được đề xuất phù hợp với bộ điều khiển kép mờ thích ứng-mạnh mẽ và có thể được sử dụng để bổ sung và thay thế cho điều khiển backstepping truyền thống.

Từ khóa: *Tay máy robot công nghiệp; điều khiển mờ kép thích nghi bền vững; điều khiển trượt; điều khiển backstepping.*

1. INTRODUCTION

For IRM then precise dynamics are not available in position to design the perfect controller. In fact, the controller of IRM is a nonlinear system with multi-input-multi-output (MIMO). System of the robot in the process of working is always affected by external disturbances, nonlinear function, payloads, etc.... to overcome this, there were many proposed controllers for example adaptive control, sustainable adaptive controller, backstepping controller and intelligent controller, etc [1-4]. Robust adaptive backstepping techniques have been developed for the construction of controllers for MIMO systems [5]. In order to design a control and tracking strategy that is appropriate for a large class of linear state response systems, investigations based on backstepping control have been proposed [6-7]. However, Backsteppinng design method still has some disadvantages. The backtepping method is really just an incremental recursive design method. To solve the disadvantage of backstepping controller, an adaptive fuzzy controller has been developed for IRM. Adaptive fuzzy controller has been added effectively to approximate nonlinear systems [8-11]. However, for most proposed adaptive fuzzy controllers, fuzzy control rules are difficult to develop appropriate control rules, associated functions and ensure system stability is a big problem that needs to be addressed. To solve this problem the author has proposed two combinations. These effective combinations are based on the advantages of fuzzy control, backstepping and sliding mode control. The first combination of multi-input fuzzy control, backstepping, and sliding mode control has developed a fuzzy backstepping sliding mode control (FBSMC) based on the design of the general back-

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stepping control method. However, in the first combination there was a chattering signal caused by the sliding mode controller. That is solved by the second combination. This combination is created by adding a single-input fuzzy controller to the FBSMC controller to create a double fuzzy backstepping sliding mode control (DFBSMC). Due the multi-input fuzzy control does a good approximation of the nonlinear function, and the single-input fuzzy controller does a good job of eliminating chattering signals in the sliding mode controller. So the DFBSMC controller proposed in this chapter uses both to approximate unknown dynamics and eliminate chattering signals. In this control method, sliding mode control and backstepping technique can be taken full advantage and both fuzzy controllers compensate for the lack of sliding mode control and backstepping technique. The stability and the ability to eliminate chattering signals were proved by Lyapunov's theorem, and the simulation results were carried out by three-link robot manipulator.

This is the latest technology that currently does not coincide with any research. A combination of multi-input fuzzy control, single-input fuzzy control, sliding mode control and backstepping control is introduced to the industrial robot manipulator (IRM). This is a new innovation in intelligent control technology for industrial robot manipulators. It contributes to the enhancement of the company's technical capabilities as demonstrated by its ability to eliminate interference signals that affect industrial robotic arms.

2. PROBLEM FORMULATION AND PRELIMINARIES

2.1. Dynamic of Industrial Robot Manipulators

Considering the dynamic equation of n-link industrial robot manipulator is given as follows [17]:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+D_e=\tau \tag{1}$$

Where:

$(q,\dot{q},\ddot{q})\in R^{n\times 1}$ are the vectors of joint position, velocity and acceleration, respectively. $M(q)\in R^{n\times n}$ is the symmetric inertial Matrix. $C(q,\dot{q})\in R^{n\times n}$ n is the vector of Coriolis and Centripetal forces. $D_e\in R^{n\times 1}$ is the bounded unknown disturbances input and the unmodeled dynamics vector. And τ is the $n\times 1$ control input vector of joints torque.

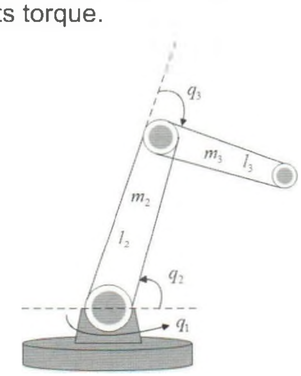

Figure 1. *Industrial robot manipulator*

For designing controller, several properties of the robot dynamics Equation (1) have been assumed as follows.

Property 1: The inertial matrix $M(q)$ is a symmetric and bounded positive matrix.

$$M(q)\le m_0 I \tag{2}$$

Where:

$m_0>0$ and $m_0\in R$.

Property 2: $\dot{M}(q)-2C(q,\dot{q})$ is skew symmetric matrix, for any vector x.

$$x^T\left[\dot{M}(q)-2C(q,\dot{q})\right]x=0 \tag{3}$$

Property 3: $C(q,\dot{q})\dot{q},\ F(\dot{q})$ is bounder as follows.

$$\left\|C(q,\dot{q})\dot{q}\right\|\le C_k\left\|\dot{q}\right\|^2 \tag{4}$$

Where:

C_k is positive constants.

Property 4: $D_e>0;\ D_e \square R^{n\square}$ is the unknown disturbance and bounded as.

$$D_e>0;\ D_e\in R^{n\times 1} \tag{5}$$

Where:

d_e is known positive constants.

2.2. Design of Fuzzy Backstepping Sliding Mode Controller

In this section, we proposed an intelligent controller which combines multi input fuzzy controller, backstepping controller and sliding mode controller to suppress the effects of the uncertainties and approximation errors. Thus, the unknown functions of robot manipulator control system are estimated, and the stability of control system can be guaranteed. The structure of the proposed fuzzy backsepping sliding mode controller (FBSMC) is described in Fig. 2.

The multi input fuzzy controller will be applied to solve the approximator of the system (1). The SMC with robust compensating effect acts as a secondary controller to ensure stability and sustainability under the different environments. The 2 step fuzzy backstepping sliding mode controller design is based on the change of coordinates.

Define.

$$\begin{cases} x_1=q \\ x_2=\dot{q} \\ y=x_1 \\ z_1=y-y_d \\ z_2=x_2-\alpha_1 \end{cases} \tag{6}$$

Where:

$y_d(t)$ is the expected angle and has second order derivative, $x_2=\dot{x}_1$, α_1 is an intermediate control and selected as:

$$\alpha_1=\dot{y}_d-\lambda_1 z_1 \tag{7}$$

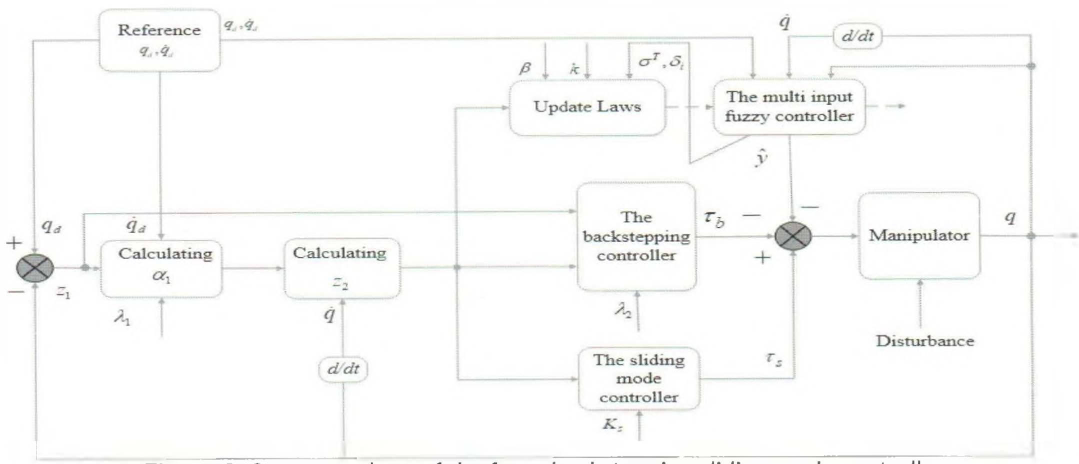

Figure 2. *Structure chart of the fuzzy backstepping sliding mode controller*

With $\lambda_1 > 0$

Step 1: By choosing the appropriate α_1, leading to the filtered tracking error $z_2(t) \to 0$, and from (6). The derivative of $z_1(t)$ can be obtained:

$$\dot{z}_1(t) = z_2 + \alpha_1 - \dot{y}_d \tag{8}$$

Consider the following Lyapunov function candidate L_1 as follows:

$$L_1 = \frac{1}{2} z_1^T z_1 \tag{9}$$

The time derivative of the Lyapunov function L_1 and using equations (6-8), one has.

$$\begin{aligned} \dot{L}_1 &= z_1^T \dot{z}_1 = z_1^T(\dot{y} - \dot{y}_d) = z_1^T(\dot{x}_1 - \dot{y}_d) = z_1^T(x_2 - \dot{y}_d) \\ &= z_1^T(z_2 + \alpha_1 - \dot{y}_d) = -\lambda_1 z_1^T z_1 + z_1^T z_2 \end{aligned} \tag{10}$$

Step 2: The dynamics equation (2.1) of three link robot manipulators can be rewritten as follows:

$$\dot{x}_2 = -M^{-1}Cx_2 - M^{-1}D_e + M^{-1}\tau \tag{11}$$

From (11) and by using $z_2(t) = x_2(t) - \alpha_1$, we can obtain:

$$\dot{z}_2 = -M^{-1}Cx_2 - M^{-1}D_e + M^{-1}\tau - \dot{\alpha}_1 \tag{12}$$

To continue our design, the adaptive control law is proposed as follows:

$$\tau = -\tau_b - \hat{y} + \tau_s \tag{13}$$

Where:

τ_b is the backstepping controller.

$$\tau_b = z_1 + \lambda_2 z_2 \tag{14}$$

With $\lambda_2 > 0$

In (13) τ_s is a SMC robust term that is used to suppress the effects of uncertainties and approximation errors, and $\hat{y}(x)$ is the approximation of the adaptive function $y(x)$ and is defined as.

$$\hat{y} = -\hat{C}\alpha_1 - \hat{M}\dot{\alpha}_1 \tag{15}$$

Follow above analysis, we propose a SMC robust term τ_s as:

$$\tau_s = K_s \operatorname{sgn}(z_2) \tag{16}$$

Where:

$K_s = diag\{K_{s1}, K_{s2}, K_{s3}\}$ and $K_s > d_e$ substituting (14) and (16) into (13), we obtain.

$$\tau = -z_1 - \lambda_2 z_2 - \hat{y} + K_s \operatorname{sgn}(z_2) \tag{17}$$

Consider the following candidate Lyapunov function:

$$L_2 = L_1 + \frac{1}{2} z_2^T M z_2 \tag{18}$$

The time derivative of L_2 is.

$$\dot{L}_2 = \dot{L}_1 + \frac{1}{2}\dot{z}_2^T M z_2 + \frac{1}{2} z_2^T \dot{M} z_2 + \frac{1}{2} z_2^T M \dot{z}_2 \tag{19}$$

From equations (6), (10), (12) and using property 3, we have.

$$\begin{aligned} \dot{L}_2 &= z_1^T z_2 - \lambda_1 z_1^T z_1 + z_2^T M(-M^{-1}Cx_2 - M^{-1}D_e \\ &\quad + M^{-1}\tau - \dot{\alpha}_1) + z_2^T C z_2 \\ &= z_1^T z_2 - \lambda_1 z_1^T z_1 \\ &\quad + z_2^T(-C\alpha_1 - M\dot{\alpha}_1 - \lambda_2 z_2 - z_1 - \sigma^T\delta) \\ &\quad + z_2^T K_s \operatorname{sgn}(z_2) - z_2^T D_e \end{aligned} \tag{20}$$

By defining $y = -C\alpha_1 - M\dot{\alpha}_1$, now (20) becomes.

$$\begin{aligned} \dot{L}_2 &= -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T(y - \sigma^T\delta) \\ &\quad + z_2^T K_s \operatorname{sgn}(z_2) - z_2^T D_e \\ &= -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T(y - \sigma^T\delta^*) \\ &\quad + z_2^T\left[\sigma^T\delta^* - \sigma^T\delta\right] + z_2^T K_s \operatorname{sgn}(z_2) - z_2^T D_e \\ &= -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T(y - \sigma^T\delta^*) \\ &\quad + z_2^T \sigma^T \tilde{\delta} + z_2^T K_s \operatorname{sgn}(z_2) - z_2^T D_e \\ \dot{L}_2 &\le -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + z_2^T(y - \sigma^T\delta^*) \\ &\quad + z_2^T \sigma^T \tilde{\delta} \end{aligned} \tag{21}$$

Using (5) and property 4, we can obtain:

$$\begin{aligned} \dot{L}_2 &\le -\lambda_1 z_1^T z_1 - \lambda_2 z_2^T z_2 + \frac{1}{2}\left(z_2^T\right)^2 + \frac{1}{2}(y - \sigma^T\delta^*)^2 \\ &\quad + z_2^T \sigma^T \tilde{\delta} \\ &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right) z_2^T z_2 + \frac{1}{2}\omega^2 + z_2^T \sigma^T \tilde{\delta} \end{aligned} \tag{22}$$

2.3. DESIGN OF DOUUBLE FUZZY BACKSTEPPING SLIDING MODE CONTROLLER

The structure of the double-fuzzy backstepping sliding mode controller (DFBSMC) is shown in Figure 2.4 below:

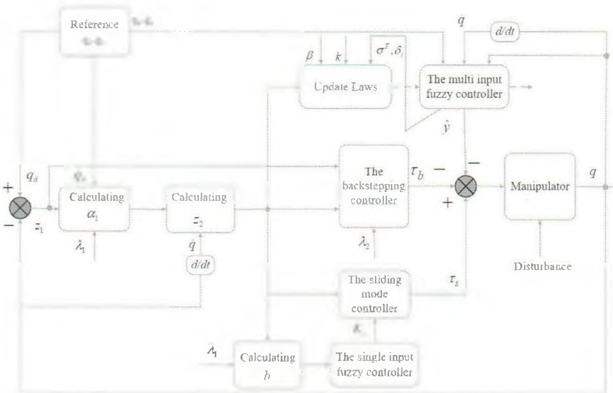

Figure 3. *Structure chart of the double-fuzzy backstepping sliding mode controller*

$$h = \frac{|\lambda_1 z_1 + \dot{z}_1|}{\sqrt{\lambda_1^2 + 1}} = \frac{|z_2|}{\sqrt{\lambda_1^2 + 1}} \quad (23)$$

As shown in Fig 3, h is given by

As seen from (23), h is non-negative, h is proportional to $|z_2|$ and the proportionality coefficient is related to the slope λ_1 of the sliding surface, to make h_i can not only reflect the magnitude of the value z_2 but also reflect the positive and negative conditions, it is necessary to improve (23), which can be rewritten as.

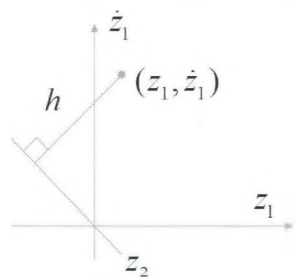

Figure 4. *Distance between current movement point and sliding surface*

$$h = \frac{z_2}{\sqrt{\lambda_1^2 + 1}}$$

The improved h is called as the generalized distance. The generalized distance h is defined as the input of the laws, switch gain K_s is defined as the output of the laws. Then, the fuzzy rules in the block "the single input fuzzy controller" (Figure 4) are shown in Table 1 below.

Table 1. *Input-output rule of the single input fuzzy controller*

The number of fuzzy rules	*h*	*Ks*
1	*NB*	*NB*
2	*NM*	*NM*
3	*NS*	*NS*
4	*Z*	*Z*
5	*PS*	*PS*
6	*PM*	*PM*
7	*PB*	*PB*

The membership functions of linguistic labels $NB, NM, NS, Z, PS, PM, PB$ for the term h are shown in Figure 5. The membership functions of linguistic labels $NB, NM, NS, Z, PS, PM, PB$ for the term K_s are shown in Figure 6.

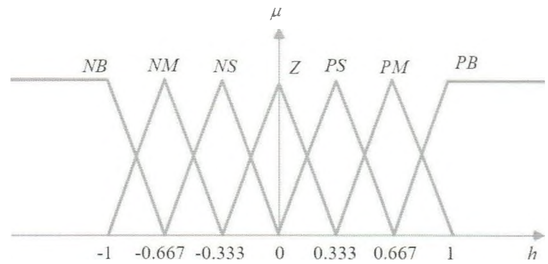

Figure 5. *Input membership functions of single input*

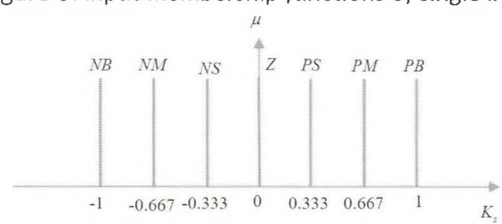

Figure 6. *Output membership functions of single input fuzzy controller*

The membership function in Figures 6 and Figures 7 is norm form. Where NB, NM, NS, Z and PS, PM, PB indicate Negative Big, Negative Medium, Negative Small, Zero and Positive Small, Positive Medium, Positive Big, respectively.

By applying the adaptive control law equation (17) to the dynamic equation (1), using the SMC function equation (16), and using the backstepping controller equation (14), the online update laws of the multi input fuzzy controller are designed as.

$$\dot{\delta} = -k\delta + \beta\left[z_2^T \sigma^T(x)\right]^T \quad (24)$$

Where:

k, β are positive adaptation rates.

3. DENONSTRATE STABLITITY ANDCAPABILITY OF ELIMINATING CHATTERING SIGNAL OF THE PROPOSED CONTROLLER

Two theorems will be proved in this section. Theorem 1 is to analyze the asymptotic stability of the closed-loop system in Figure 3 which is described by equation (12). Theorem 2 involves analyzing the ability of eliminating chattering signal of the proposed controller is shown in Figure 4.

Theorem 1: Consider a three-link industrial robot manipulator represented by (1). If the DFBSMC adaptive update laws are designed as (24), the SMC is give by (16), and backstepping controller (14). The adaptive control law designed in (12), then the tracking error and the convergence of all the system parameters can approached to zero asymptotically.

Proof: Consider the following candidate Lyapunov function:

$$L = L_2 + \frac{1}{2\beta}\tilde{\delta}^T\tilde{\delta} \tag{25}$$

With $\beta > 0$

The time derivative of L is

$$\dot{L} = \dot{L}_2 - \frac{1}{\beta}\tilde{\delta}^T\dot{\delta} \tag{26}$$

Similar to the derivations in step 2, one has.

$$\begin{aligned}\dot{L}_2 &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right) z_2^T z_2 + \frac{1}{2}\omega^2 + z_2^T\sigma^T\tilde{\delta} \\ &\quad -\frac{1}{\beta}\tilde{\delta}^T\dot{\delta} \\ &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right) z_2^T M M^{-1} z_2 + z_2^T\sigma^T\tilde{\delta} \\ &\quad -\frac{1}{\beta}\tilde{\delta}^T\dot{\delta} + \frac{1}{2}\omega^2\end{aligned} \tag{27}$$

From property 1 and the adaptive law (25), now (27) becomes.

$$\begin{aligned}\dot{L} &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right)\frac{1}{m_0} z_2^T M z_2 \\ &\quad + \frac{k}{\beta}\tilde{\delta}^T\delta + \frac{1}{2}\omega^2 \\ &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right)\frac{1}{m_0} z_2^T M z_2 \\ &\quad + \frac{k}{2\beta}(2\delta^{*T}\delta - 2\delta^T\delta) + \frac{1}{2}\omega^2 \\ &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right)\frac{1}{m_0} z_2^T M z_2 \\ &\quad + \frac{k}{2\beta}(\delta^{*T}\delta^* - \delta^T\delta) + \frac{1}{2}\omega^2 \\ &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right)\frac{1}{m_0} z_2^T M z_2 \\ &\quad + \frac{k}{2\beta}(-\delta^{*T}\delta - \delta^T\delta) + \frac{k}{\beta}\delta^{*T}\delta^* + \frac{1}{2}\omega^2\end{aligned} \tag{28}$$

Since $-\delta^{*T}\delta^* - \delta^T\delta \le -\frac{1}{2}\tilde{\delta}^T\tilde{\delta}$, now (28) becomes

$$\begin{aligned}\dot{L} &\le -\lambda_1 z_1^T z_1 - \left(\lambda_2 - \frac{1}{2}\right)\frac{1}{m_0} z_2^T M z_2 - \frac{k}{2\beta}\left(\frac{1}{2}\tilde{\delta}^T\tilde{\delta}\right) \\ &\quad + \frac{k}{\beta}\delta^{*T}\delta^* + \frac{1}{2}\omega^2\end{aligned} \tag{29}$$

Denote $\xi_m = \mathrm{Min}\left\{2\lambda_1, (2\lambda_2 - 1)\frac{1}{m_0}, \frac{k}{2}\right\}$ and $\xi_0 = \frac{k}{\beta}\delta^{*T}\delta^* + \frac{1}{2}w^2$.

We have

$$\begin{aligned}\dot{L} &\le -\xi_m\left(\frac{1}{2}z_1^T z_1 + \frac{1}{2}z_2^T M z_2 + \frac{1}{2\beta}\tilde{\delta}^T\tilde{\delta}\right) + \xi_0 \\ &\le -\xi_m L + \xi_0\end{aligned} \tag{30}$$

Integrating $\dot{L}$ with respect to time as follows: Then

$$L(t) \le L(0) + \frac{\xi_0}{\xi_m} \tag{31}$$

Moreover, by (31), we can further obtain

$$\frac{1}{2}z_1^2(t) = \frac{1}{2}(y(t) - y_d(t))^2 \le L(t) \le L(0) + \frac{\xi_0}{\xi_m} \tag{32}$$

Equation (30) implies that there exists T which for all $t > T$, the tracking error z_1 satisfies.

$$|z_1| \le \sqrt{\frac{\xi_0}{\xi_m}} \tag{33}$$

Following the above design procedures, stable analysis guarantees that all the signals in the closed-loop system are bounded in mean square. Furthermore, the tracking error can be made arbitrarily small by choosing the appropriate design parameters.

Theorem 2: Consider a three-link robot manipulator represented by (1). If the adaptive control law is defined as (12), the generalized distance h is defined as (24). If the fixed parameter K_s in equation (12) is substitute by a replacement cost based on the magnitude of the generalized distance h through the single input fuzzy controller, then the chattering signal in the system will be completely eliminated.

Proof: From equation (12), it is clear that the main component causing the chattering phenomenon in the system is the function $K_s\,\mathrm{sgn}(z_2)$. To overcome this phenomenon, we add a fuzzy processing element in the controller to eliminate the $sign$.

By the focal defuzzification method parameter K_s is defined:

$$K_s = \frac{\sum_{i=1}^{7}\beta_i K_s^i}{\sum_{i=1}^{7}\beta_i} \tag{34}$$

In there b_i is the correctness of the i^{th} rule:

$$K_s = \frac{\sum_{i=1}^{7}\beta_i K_s^i}{\sum_{i=1}^{7}\beta_i} \tag{35}$$

From (34) and (35) we obtain:

$$\lim_{z_2 \to 0} K_s = \lim_{z_2 \to 0} \frac{\sum_{i=1}^{7} \beta_i K_s^i}{\sum_{i=1}^{7} \beta_i} = 0 \quad (36)$$

From (36) deduce.

$$\lim_{z_2 \to 0} K_s \operatorname{sgn}(z_2) = 0 \quad (37)$$

According to theorem 1 we have.

$$\lim_{t \to \infty} z_2 = 0 \quad (38)$$

From (37) and (38) we deduce.

$$\lim_{t \to \infty} K_s \operatorname{sgn}(z_2) = 0 \quad (39)$$

According to (39) when time t tends to ∞, function $K_s \operatorname{sgn}(z_2)$ is completely eliminated in adaptive control law (12). Thus, chattering signal at the tracking position has been completely eliminated in the proposed controller.

4. SIMULATION RESULTS

Adopting control algorithm for three-link robot manipulator. Matlab software is used to study the control algorithm proposed by simulation. The parameter of the robot arm is shown as follows:

$$l_2 = 0.5m; l_3 = 0.5m; r_2 = 0.25m; r_3 = 0.25;$$

$$m_2 = 10kg; m_3 = 10kg; I_1 = 0.08kg\,m^2;$$

$$I_2 = 0.12kg\,m^2; I_3 = 0.12kg\,m^2.$$

The designed tracking trajectory is

$$q_{d1} = 0.1\sin t; q_{d2} = 0.1\sin t; q_{d3} = \frac{\pi}{6}\sin t$$

The initial condition is $q = [0.09, -0.09, 0]$

The parameter values used in the adaptive control system are chosen for the convenience of simulations as follows:

$$\lambda_1 = 2; \lambda_2 = 5; k = 1.5; \beta = 2;$$

$$K_s = diag[0.1, 0.1, 0.1]$$

The simulation results are shown in the following figures. Figure 7 shows the approximate $\hat{y}$ of the multi input fuzzy controller when compared to the actual y. Figures 8 and 9 show the tracking trajectory of the fuzzy backstepping sliding mode control and the double-fuzzy backstepping sliding mode control respectively. Figures 10 and 11 show the control efforts of the fuzzy backstepping sliding mode control and the double-fuzzy backstepping sliding mode control respectively.

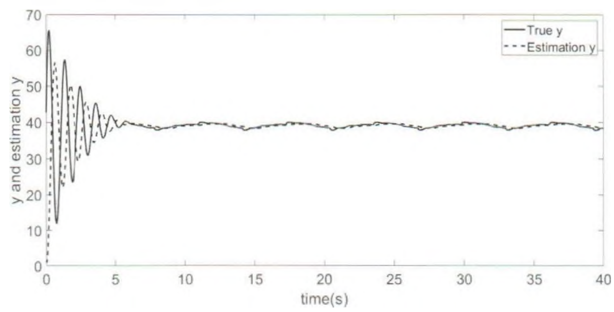

Figure 7. *y and estimation y*

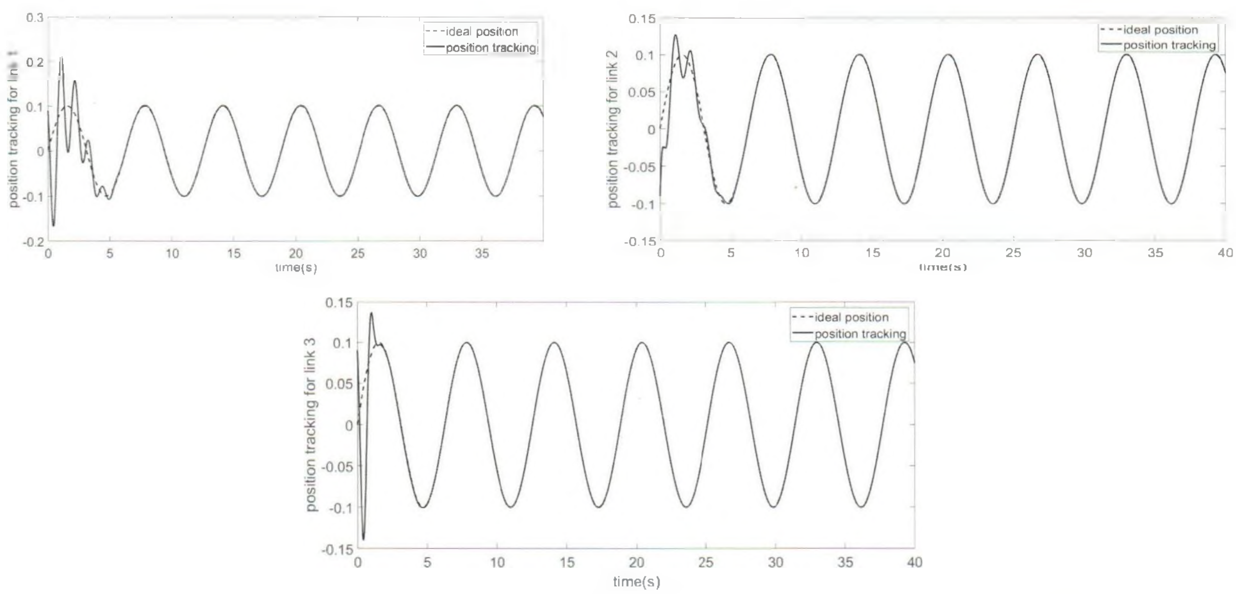

Figure 8. *The position tracking of FBSMC controllerBased on the simulation results, some conclusions can be reached as follows. In Figure 8, we can see that $\hat{y}$ approximates best from 5 s and errors within acceptable range.*

From Figures 8 and 9, it can be seen that the FBSMC and DFBSMC both follow the desired trajectory of the IRM. However, compared to the FBSMC control, the DFBSMC control has improved the response and reduced the adjustment time. The link 1 trajectory of the FBSMC controller almost completely follows the desired trajectory at 6th seconds, while the link 2 trajectory of the DFBSMC controller follows the desired trajectory at the 5th second. Similarly, the FBSMC controller's link 2 trajectory follows the design trajectory at

5th seconds. While the trajectory of link 2 of the dfbsmc controller follows the design trajectory at the 4th second. the FBSMC controller's link 3 trajectory follows the design trajectory at 3th seconds. While the trajectory of link 3 of the DFBSMC controller follows the design trajectory at the 2th second.

From Figure 10 and Figure 11, it can be seen that the chattering signal still exists in the fbsmc controller while the control input of the dfsmc controller has partially removed the chattering signal. The amplitude of the chattering signal from the control inputs of links 1, 2 and 3 illustrates the ability to eliminate the chattering signal of the DFSMC controller compared to the FBSMC controller.

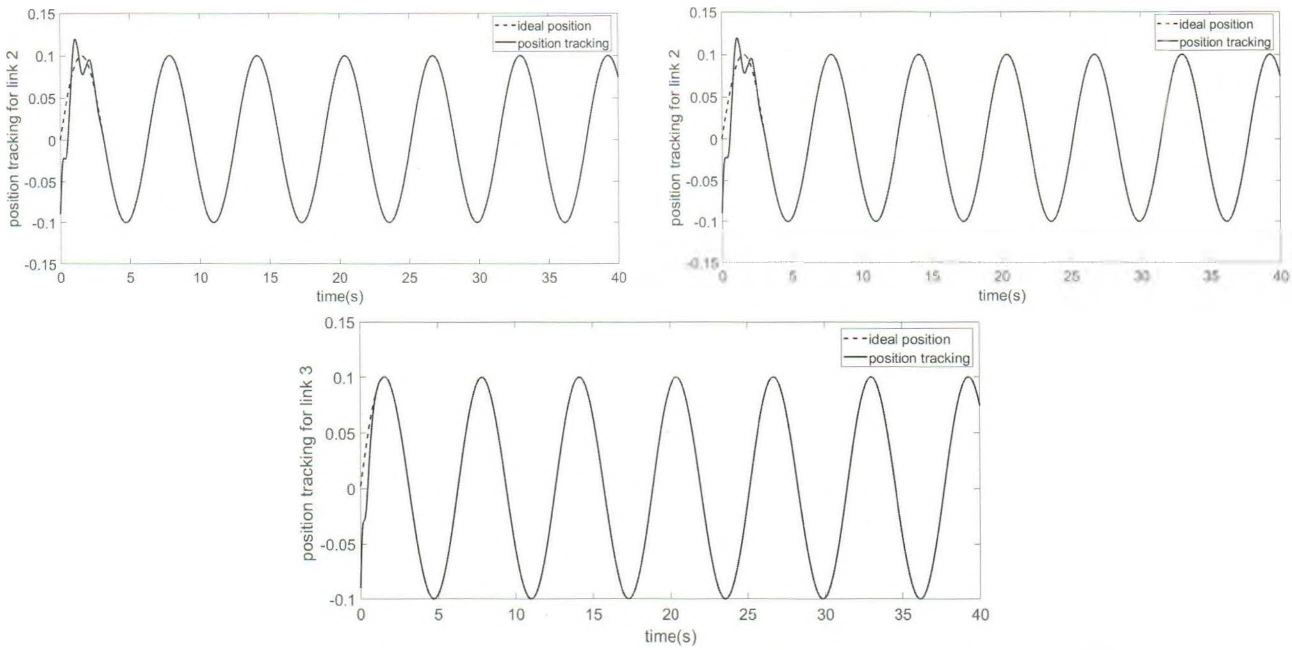

Figure 9. *The position tracking of DFBSMC controller*

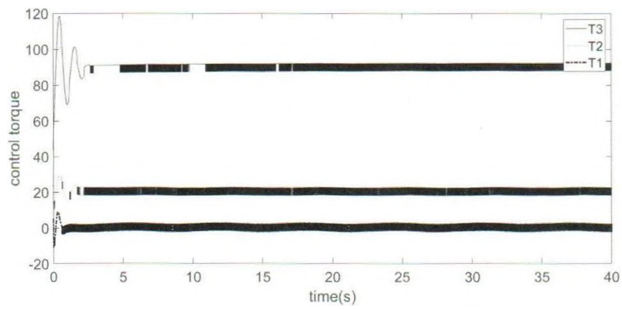

Figure 10. *The control torque of FBSMC controller*

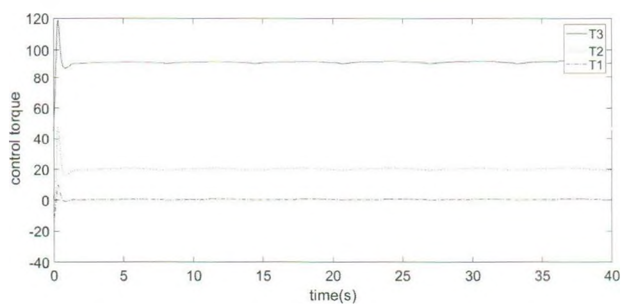

Figure 11. *The control torque of DFBSMC controller*

5. CONCLUSIONS

In this research, a combination of multi-input fuzzy control, single-input fuzzy control, sliding mode control and backstepping control has ensured stability and stability in disturbed and changing environments. By using the stability theory of Lyapunov, the authors have proved that the system is always stable throughout the workspace. Moreover, the effectiveness of the controller is also demonstrated through simulation and experiment results when comparing the proposed controller with FBSMC and DFBSMC. The simulation results show that the convergence speed, braking ability, grip error, stability, fast response, overshoot of the proposed controller DFBSMC are better than the FBSMC controller.

Currently, microprocessors and microcontrollers perform fast computations, so complex problems are nothing to worry about.

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