Fuzzy-Terminal Sliding Mode Control of a Flexible Link Manipulator

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Abstract: In this study, a terminal sliding mode controller is introduced, for trajectory tracking control, of a flexible link robot manipulator. Two important parameters are considered; angle of the link and tip deflection. To demonstrate the effectiveness of the developed controller, control gain parameters in the sliding mode controller are determined by using Fuzzy Logic Control law. Another important feature of the developed controller is that it is robust against external disturbances. Stability analysis of the system is guaranteed by the Lyapunov theory. Trajectory tracking errors, angles and tip deflection of the links are investigated for two different trajectories. When the results are examined, it is seen that the developed controller, with fuzzy logic, is effective, even if there are external disturbances and parametric uncertainties in the system.

Keywords: flexible link manipulator; fuzzy controller; terminal sliding mode controller

1 Introduction

In recent decades, robot technology has started to serve in many fields. Especially, are the robots used in industry, that aim at obtaining high efficiencies. The rigid design of the robots, restricts application areas and the desired efficiency cannot be obtained from these types of rigid link robots. For this reason, instead of rigid robots, flexible manipulators are currently preferred. Li and Huang [1], designed an adaptive fuzzy terminal sliding mode controller for robotic manipulator. The control strategy is based on a Lyapunov function. Along with the fuzzy logic control method, they significantly reduced the chattering problem. Doğan et al. [2] examined the purpose of their work as developing an adaptive-robust controller for the two-link flexible robot. They used the dynamic state feedback controller to suppress elastic vibrations. This model approach has been adjusted adaptively for unknown external disturbances. Hasan et al. [3] have developed a new fuzzy logic controller, taking into account the problem of inadequate classical control methods due to the nonlinear dynamics of flexible robots. The results were compared with the LQR controller and it was understood that the newly developed controller give better results. Shaheed and Tokhi [4], presented an investigation into the development of a closed-loop vibration control strategy for flexible manipulators. First, they introduced a proportional-derivative feedback control technique then they designed a command-filter vibration controller. They used low-pass and band-stop elliptic filters in the control law. They applied this developed controller to one link flexible manipulator. He et al. [5] deals with the problem of control design problem of flexible link manipulators. They designed an output feedback controller. The result of the study has been proven analytically and experimentally. Khairudin et al. [6] studied the dynamic modelling and characterization of a two-link flexible robot manipulator. They used Euler – Lagrange and assumed modes methods to design the dynamic model of the system. In case of a load in the system, they discussed the system response. Lee and Vukovich [7] designed the fuzzy logical control method in three stages. For the vibration and position control, the fuzzy logic controller was applied to one link flexible robot and the experimental results were examined. Tinkir et al. [8], proposed neuro-fuzzy control strategy for one link flexible manipulator. At first, a CAD model of the flexible link robot was created and the model was transferred to the SimMechanics program. They developed a fuzzy logical control method for the model's vibration control. Akyüz et al. [9], designed the cascade fuzzy logic controller to single link flexible joint manipulator. A number of experiments have been carried out to prove the effectiveness of the controller. Abdullahi et al. [10] presented and compared the fuzzy logic control and pole placement control of a rigid-flexible link manipulator. The input of the fuzzy logic control was the joint angle error and its derivative and the output of the controller was the controller signal. Computer simulations were performed and controllers were compared. Rouhani and Erfanian [11] developed a new adaptive fuzzy terminal sliding mode controller for uncertain nonlinear systems. The proposed controller is a combination of fuzzy logic control and terminal based gradient descent (GD) algorithm. Fuzzy logic controller is designed to estimate the nonlinear dynamics of the system and terminal based GD is used to update the parameters. This developed controller is applied to a two link robot manipulator. From the simulation results, it is seen that the tracking errors are converged to zero in a short time. Also proposed controller is applied to control of joint movement generated by functional electrical stimulation. Experimental results also proved that the controller is effective. Moghaddam et al. [12] designed a disturbance-observer-based fuzzy terminal sliding mode controller for multi-input and multi-output systems. They aimed to minimize the tracking error and to eliminate the external disturbances by disturbance observer. Also they developed this proposed controller to reduce chattering problem of uncertain systems. The Lyapunov Theorem is used to guaranteed the stability of the system. They applied this controller to an Unmanned Aerial Vehicle (UAV) to show the effectiveness of the controller. Wang et al. [13] presented a robust adaptive fuzzy terminal sliding mode controller with low pass filter. They wanted to minimize the trajectory tracking error and to eliminate the external disturbances of the systems. Also, the chattering problem is solved by continuous control law. This proposed control law was applied to chain-series robot manipulator. Experimental results showed the effectiveness of the controller. Ba et al. [14] proposed position controller that combines fuzzy terminal sliding mode controller and time delay estimation. They designed the fuzzy controller to adjust the parameters in the terminal sliding mode control law. External disturbances in the system is also eliminated by time delay estimation. They applied proposed controller to hydraulic drive unit test platform. From the experimental results it is clearly seen that, the developed controller improves position control and robust to external disturbances. Vo et al. [15] developed a controller that the combination of non-singular fast terminal sliding variable and a continuous control algorithm. They also used fuzzy logic controller to update control law. The uncertainties of the system is eliminated without any chattering problem by switching control law. The robustness and the stability of the system is guaranteed by Lyapunov theory. Then, the 3-dof Puma 560 model was used to show the effectiveness of the controller. From the numerical results, it is understood that, the robot performs joint position tracking with minimum errors.

2 Terminal Sliding Mode Control Law for Flexible Link Manipulator

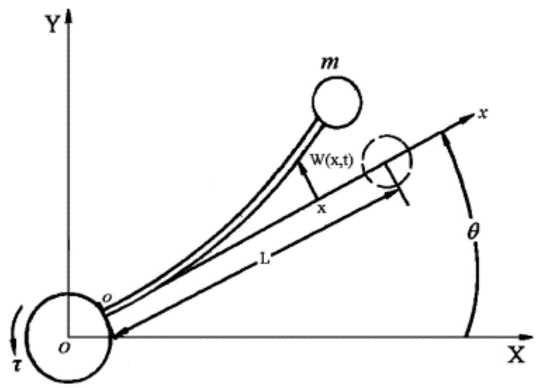


Figure 1
Flexible link manipulator [16]

The flexible link manipulator is given as in Figure 1 and the parameters of the manipulator is given in Table 1.

The model is considered as a cantilever beam model that can rotate around the z axis. w denotes the elastic deflection of the beam at the x point. Deviation is found by accepted modes method.

Table 1
Parameters of the manipulator [17]

P	Density of the link	0.7597	kgm^{-1}
L	Length of the link	0.22	M
EI	Bending stiffness	2.69	Nm^2
I_z	Moment of inertia	0.0007424	kgm^2

$$w(x,t) = \phi(x)\,q(t) \tag{1}$$

In the equation, q is the generalized coordinate corresponding to the vibration mode, and the mode is the shape function. Coordinate of any P on the link is: [17]

$$P = \begin{bmatrix} P_x \\ P_y \end{bmatrix} = \begin{bmatrix} x\cos\theta - w(x,t)\sin\theta \\ x\sin\theta + w(x,t)\cos\theta \end{bmatrix} \tag{2}$$

Dynamic model of a flexible link manipulator can be written in a Matrix form as:

$$\begin{bmatrix} M_{\theta\theta} & M_{\theta q} \\ M^T{}_{\theta q} & M_{qq} \end{bmatrix}\begin{bmatrix} \ddot\theta \\ \ddot q \end{bmatrix} + \begin{bmatrix} \dot q^T M_{qq} q & \dot\theta q^T M_{qq} \\ -\dot\theta q^T M_{qq} & 0 \end{bmatrix}\begin{bmatrix} \dot\theta \\ \dot q \end{bmatrix} + \begin{bmatrix} 0 \\ K_q q \end{bmatrix} = \begin{bmatrix} u \\ 0 \end{bmatrix} \tag{3}$$

Where,

$$M_{\theta\theta} = I_t + I_z + m_q \qquad M_{\theta q} = M^T{}_{\theta q} = m_{\dot q\dot\theta} \qquad M_{qq} = m_q$$

$$K_q = EI\int_0^l \phi''^2 dx \quad I_t = \rho\int_0^l (x)^2 dx + I_z \quad m_{\dot q\dot\theta} = \rho\int_0^l \phi(x)dx \quad m_q = \rho\int_0^l \phi^2 dx \tag{4}$$

The Equation (3) is written in the form as:

$$M(q)\ddot q + C(q,\dot q)\dot q + G(q) = Y(q,\dot q,\ddot q)\eta \tag{5}$$

Where,

$$Y = \begin{bmatrix} \ddot\theta & \ddot\theta + \dot q^T q\dot\theta + \dot\theta q^T \dot q & 0 & 0 \\ 0 & \dot q - \dot\theta q^T \dot\theta & \ddot\theta & q \end{bmatrix} \tag{6}$$

and

$$\eta = [\eta_1 \quad \eta_2 \quad \eta_3 \quad \eta_4]^T \tag{7}$$

Considering the equation 7, η values are given as:

$$\eta_1 = \rho\int_0^l (x)^2 dx + I_z \quad \eta_2 = \rho\int_0^l \phi^2 dx \quad \eta_3 = \rho\int_0^l \phi(x)dx \quad \eta_4 = EI\int_0^{l_1} \phi''^2 dx \tag{8}$$

Considering the terminal sliding mode control [18], the nominal control law is given for a flexible manipulator as:

$$\tau_0 = M_0(q)\ddot q_r + C_0(q,\dot q)\dot q + g_0 - Ks^r \tag{9}$$

The $\dot{q}_r$ and $\ddot{q}_r$ is given as:

$$\dot{q}_r = \dot{q}_d - \Lambda \tilde{q}^p \text{ and } \quad \ddot{q}_r = \ddot{q}_d - p\Lambda \mathrm{diag}\left[\tilde{q}_1^{p-1}.......\tilde{q}_n^{p-1}\right]\dot{\tilde{q}}; \tag{11}$$

The control gain parameters Λ and K are defined below:

$$\Lambda = \mathrm{diag}\left[\lambda_1,.......,\lambda_n\right]\rangle 0 \text{ and } K = \mathrm{diag}\left[k_1,.......,k_n\right]\rangle 0 \tag{12}$$

The other parameters are:

$$\frac{1}{2}\langle p \le 1;\ 0\langle r \le 1;\ p,r = \frac{z_1}{z_2};\ z_1, z_2 \in Z_+;\ z_1 \le z_2 \tag{14}$$

and s is the terminal sliding variable defined as [18]:

$$s = \dot{\tilde{q}} + \Lambda \tilde{q}^p \tag{15}$$

Then, the nominal control law (9) can be written in the following form as:

$$\tau_0 = Y_r \eta_0 - K s^r \tag{16}$$

Where,

$$Y_r = \begin{bmatrix} \ddot{\theta}_r & \ddot{\theta}_r + \dot{q}_r{}^T q \dot{\theta}_r + \dot{\theta}_r q^T \dot{q}_r & 0 & 0 \\ 0 & \dot{q}_r - \dot{\theta}_r q^T \dot{\theta} & \ddot{\theta}_r & q \end{bmatrix} \tag{17}$$

The nominal fixed parameters are given as:

$$\eta_0 = \left[\eta_{10} \quad \eta_{20} \quad \eta_{30} \quad \eta_{40}\right]^T \tag{18}$$

Then, the following control law is proposed in terms of the nominal control law as:

$$\tau = \tau_0 + Y_r \xi \tag{19}$$

$$= Y_r\left(\eta_0 + \xi\right) - K s^r$$

ξ is the control input and designed to provide robustness to parametric uncertainty $\tilde{\eta}$. And $\tilde{\eta}$ is defined as; $\tilde{\eta} = \eta_0 - \eta$

Here, η_0 is the nominal parameters, represents the loaded state of the robot and η represents the unloaded parameters. If we add a load of 10% of the robot's weight to the end of the robot and if we change the length of the robot arm by 10%, parameter uncertainty in the system is defined as follows.

Table 2

$\tilde{\eta}$ values

$\tilde{\eta}_1$	$\tilde{\eta}_2$	$\tilde{\eta}_3$	$\tilde{\eta}_4$
0.006	0.6453	0.08	25962.9

Along with the uncertainties shown in Table 2, the uncertainty parameter is selected as follows:

$$\|\tilde{\eta}\| = \sum_{i=1}^{4}(\eta_i + \eta_0) \le \rho^2 \qquad (21)$$

Thus ρ=25963

And, the additional control input w is defined as:

$$\xi = \begin{cases} -\rho \dfrac{Y^T s}{\|Y^T s\|} & \text{if} \quad \|Y^T s\| \rangle 0 \\ 0 & \text{if} \quad \|Y^T s\| = 0 \end{cases} \qquad (22)$$

Considering the Eq. 5, 16 and 20, the following equation is obtained:

$$M(q)\dot{s} = Y(q,\dot{q},\dot{q}_r\ddot{q}_r)(\tilde{\eta} + \xi) - Ks^r \qquad (23)$$

Where, $\tilde{\eta} = \eta_0 - \eta$ $\tilde{M} = M_0 - M$ $\tilde{C} = C_0 - C$ $\tilde{G} = G_0 - G$. In order to show the stability of the uncertain system, the following Lyapunov function is given:

$$V(t) = \frac{1}{2}s^T M s \qquad (24)$$

The time derivative of the Lyapunov function is:

$$\dot{V}(t) = s^T M \dot{s} \qquad (25)$$

Considering the Equation 23 and 25, the time derivative of the Lyapunov function (24) is obtained as:

$$\dot{V}_1(t) = -s^T K s^r + s^T Y(\tilde{\eta} + \xi) \qquad (26)$$

The relations between the Lyapunov function and the first right-hand term in Eq. (26) are given as:

$$s^T K s^r = \sum_{i=1}^{n} k_i s_i^{r+1} \qquad (27)$$

$$\ge \alpha \left\{ \sum_{i=1}^{n} \frac{1}{2} \bar{m} s_i^2 \right\}^n \qquad (28)$$

$$\ge \alpha V_i^n \qquad (29)$$

Where,

$$n = \frac{(1+r)}{2}; \alpha = k_{min}\left\{\frac{2}{\bar{m}}\right\}; \quad k_{min} = min_i\{k_i\} \qquad (30)$$

From Equation (22), There are two cases for the second term of Equation (26). If $\left\|Y^T s\right\| = 0$, the second term in Eq. (26) will be zero, that is $s^T Y(\tilde{\eta} + \xi) = 0$. If $\left\|Y^T s\right\| > 0$, the second term in Equation (22) will be equal or less than zero.

$$s^T Y\left(\tilde{\eta} + \xi\right) = s^T Y \left(\tilde{\eta} - \rho \frac{Y^T s}{\left\|Y^T s\right\|}\right) \tag{31}$$

$$\leq \left\|s^T Y\right\| \left(\left\|\tilde{\eta}\right\| - \rho\right)$$

$$\leq 0$$

From Eq. (29) and Eq. (31), the following equation is obtained.

$$\dot{V}_1(t) \leq \alpha V_1^{\eta} \tag{32}$$

The rest of the proof is given [18].

3 Fuzzy Logic Control

Fuzzy logic control strategy has its own definitions by membership functions. These membership functions are triangular, trapezoidal or bell curved shape. They take the values between [0,1].

Fuzzy Logic Controller consists of three stages (Fuzzification, Rule Evaluation and Defuzzification). In the Fuzzification stage, membership functions are defined for the variables, certain values are converted to fuzzy values. In the rule evaluation stage, rules are determined in accordance with the specified input and output parameters. And the final stage, fuzzy values are converted to certain values.

In this study, the inputs are the trajectory tracking error of the links (e1 and e2). The outputs are the p and r parameters of the terminal sliding mode controller. Block diagram of proposed fuzzy logic controller is shown in Fig. 2. Linguistic variables which implies inputs and outputs have been classified as: NO, NH, Z, PH, PO. Inputs are all normalized in the interval of [-1, 1] as shown in Fig. 3. And also outputs (p and r) are normalized in the interval of [0.5, 1] and [0, 1] shown in Fig, 4 and Fig. 5. The ranges of inputs and outputs are determined by trial and error method. The relationship between input and output has been obtained with the rule table. (Table 3)

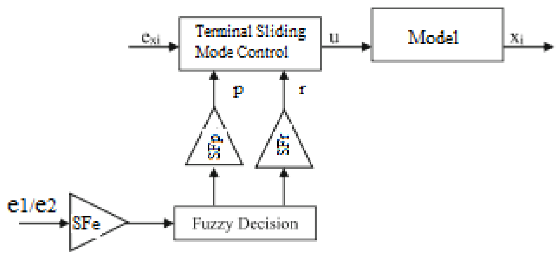


Figure 2
Block diagram of fuzzy logic controller

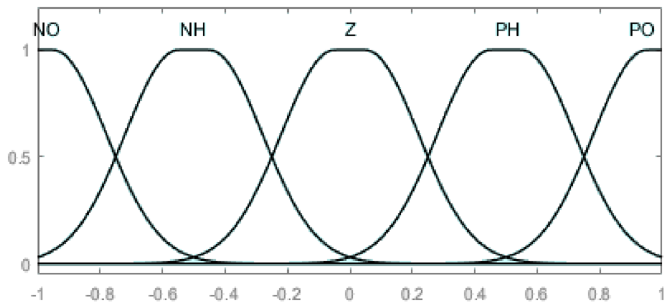


Figure 3
Membership functions of inputs (e_1, e_2)

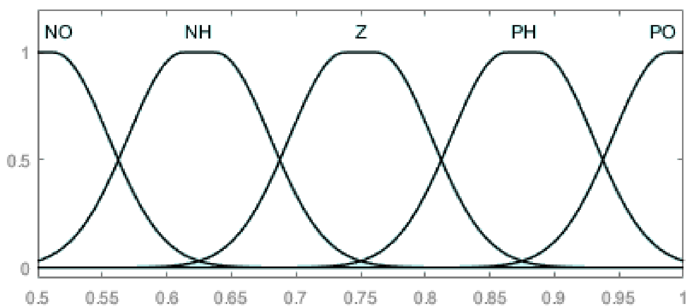


Figure 4
Membership functions of output (p)

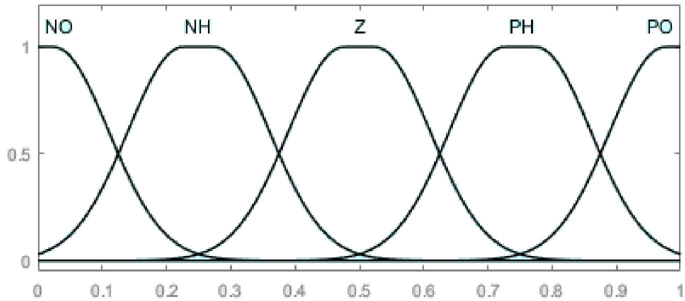


Figure 5
Membership functions of output (r)

Table 3
Decision table

e_1\ e_2	NO	NH	Z	PH	PO
NO	NO	NO	NH	Z	Z
NH	NH	NH	Z	Z	PH
Z	NH	Z	Z	PH	PH
PH	Z	Z	PH	PH	PO
PO	Z	PH	PH	PO	PO

Table 3 shows the rule table between input and output. This table was created by trial and error method and should be interpreted as follows:

If the error of the first link is NO and the error of the second link is NO, then, the parameter p and r is NO.

If the error of the first link is NO and the error of the second link is NH, then, the parameter p and r is NO.

If the error of the first link is PO and the error of the second link is PH, then, the parameter p and r is PO.

If the error of the first link is PO and the error of the second link is PO, then, the parameter p and r is PO.

4 Results

In this study, terminal sliding mode controller and fuzzy-terminal sliding mode controller was applied to flexible link manipulator. The aim of this study is to minimize the displacement of the end point of the manipulator. Two different trajectories are used in order to analyze the performance of the controller. First, a bump trajectory in Fig. 6 is used and the results are presented in Figures 7-11.

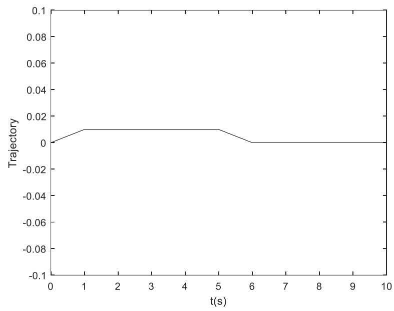
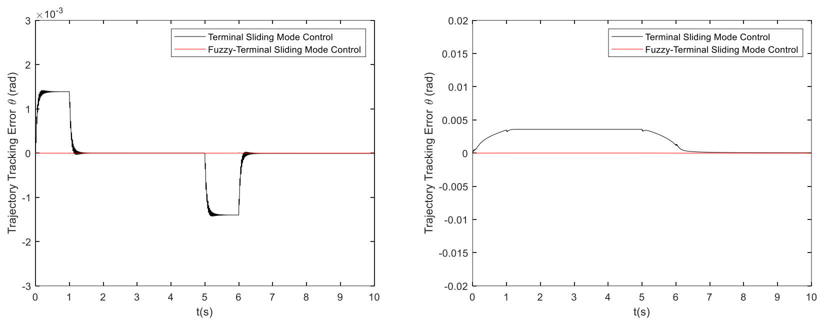


Figure 6
Desired trajectory

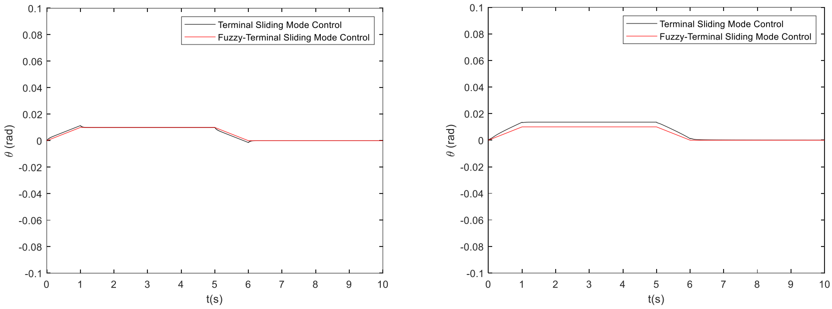
Figure 7 shows trajectory tracking error of θ over time both terminal sliding mode controller and fuzzy-terminal sliding mode controller. It is seen that the error is very small for both controllers. In the Figure 7a, the trajectory tracking error is about 1.5×10^{-6} rad for both controllers. Even if the external disturbance is involved, the trajectory tracking error is about 0.002 rad in terminal sliding mode controller. As shown in Figure 7b it is seen that the fuzzy logic controller reduces the trajectory tracking error and brings the tracking error to almost zero.



(a) (b)

Figure 7
Trajectory tracking error of angle θ with control parameters λ=diag (10 10) and K=diag(10 10)
a) Without disturbances b) With a disturbance torque

The time history of θ is given in Figure 8. When two figures are examined, it is seen that both controllers show a similar trend when there are no external disturbances. The effectiveness of the fuzzy controller seems clearly in the case of external disturbances. (Fig. 8b)



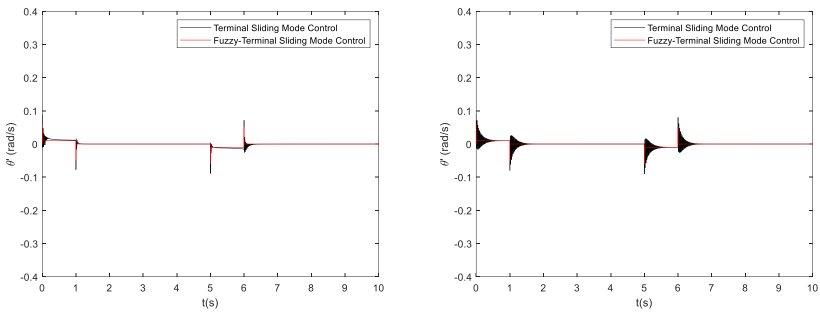
(a) (b)

Figure 8

Angle θ over time with control parameters λ=diag(10 10), K=diag(10 10)

a) Without disturbances b) With a disturbance torque

In Figure 9, the time derivative of θ is given. The system moves in regular regime with amplitudes of maximum 0.1 rad/s. In the case of external disturbances, it is seen that small chattering occurs in the terminal sliding mode controller. This problem is eliminated by the fuzzy logic controller. In particular, the efficiency of the fuzzy logic controller is clearly seen, in the graph in the case of external disturbances.



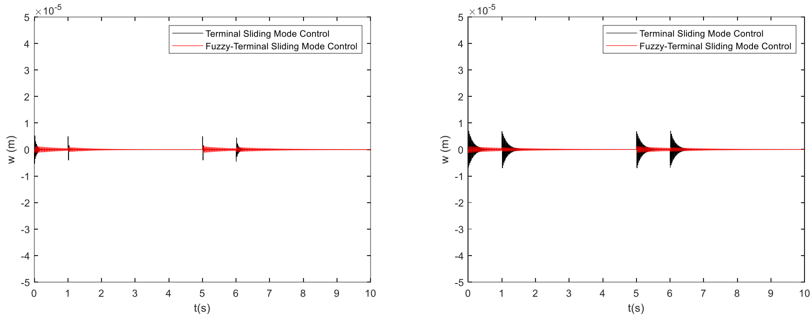
(a) (b)

Figure 9

Time derivative of angle θ over time with control parameters λ=diag(10 10), K=diag(10 10)

a) Without disturbances b) With a disturbance torque

Fig. 10 shows the response of flexible link endpoint displacement. The link returns to its former position in a short time with a deviation of maximum 0.1×10^{-6} meters. The displacement of the endpoint does not change greatly when external disturbances are involved.



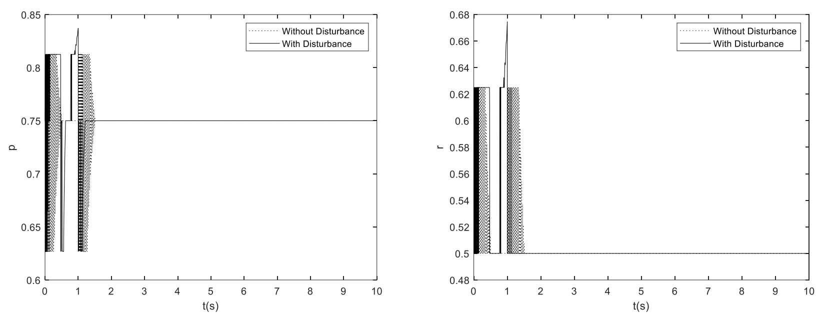
(a) (b)

Figure 10

Tip deflection w with control parameters λ=diag (10 10), K=diag(10 10)

a) Without disturbances b) With a disturbance torque

Figure 11 shows the change of the control parameters p and r with respect to time when fuzzy logic controller is used. Fuzzy logic controller provides the most accurate result by updating the control parameters according to the changes in the system. A certain limit is determined and the parameters are updated within those limits.



(a) (b)

Figure 11

Control parameter ‘p’ over time - Control parameter ‘r’ over time λ=diag (10 10), K=diag(10 10)

Sine wave trajectory in Figure 12 is used in order to analyze the performance of the controller. The results are given in Figures 13-17.

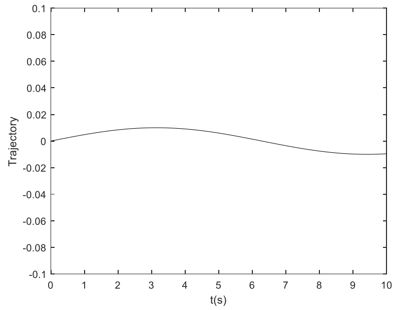
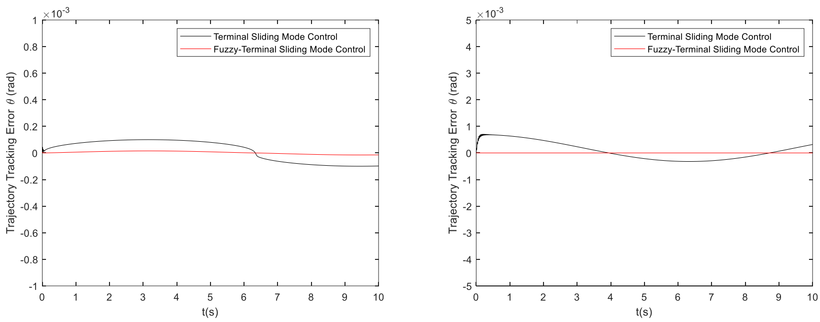


Figure 12
Desired trajectory

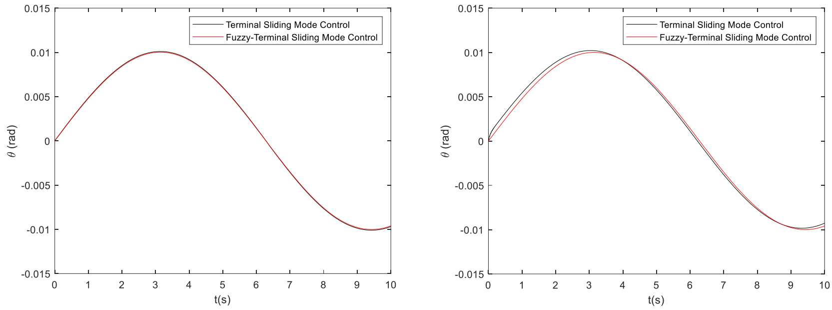
As seen in Figure 13, trajectory tracking error is small for both controllers. When external disturbances are included, the trajectory tracking error increases very little. (Fig. 13b) But even this is within tolerable limits. As shown in Figure 13, the fuzzy-terminal sliding mode controller is effective in both cases.



(a) (b)

Figure 13
Trajectory tracking error of angle θ with control parameters λ=diag (10 10) and K=diag(10 10)
a) Without disturbances b) With a disturbance torque

The time-dependent variation of θ is shown in Figure 14. When the figures are examined, it is seen that the model tracks the trajectory smoothly. The effectiveness of the fuzzy controller seems clearly in the case of external disturbances.



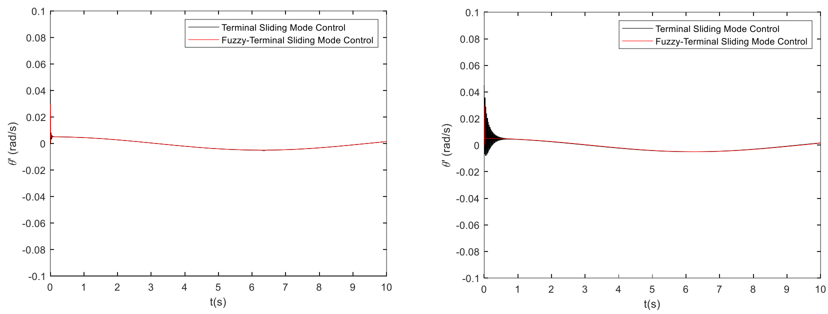
(a) (b)

Figure 14

Angle θ over time with control parameters λ=diag(10 10), K=diag(10 10)

a) Without disturbances b) With a disturbance torque

The time derivative of θ is shown in Figure 15. Both controllers appear to behave similarly when there are no external disturbances. And the highest value is around 0.04 rad/s. (Fig. 15a) In the case of external disturbance, it seems that the terminal sliding mode controller is slightly more affected but recovers quickly. The terminal sliding mode controller, on the other hand, seems to be slightly affected by the external disturbances. (Fig. 15b)



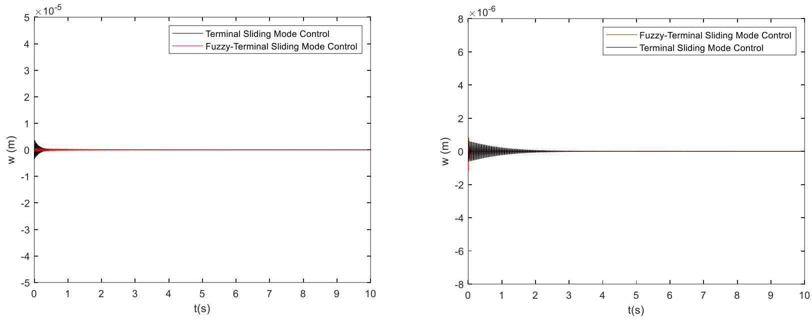
(a) (b)

Figure 15

Time derivative of angle θ over time with control parameters λ=diag(10 10), K=diag(10 10)

a) Without disturbances b) With a disturbance torque

One of the most important criteria in the model, is the displacement of the endpoint. Figure 16 shows the tip deflection of the model for both controllers and with and without external disturbance. In the Figure 16a, without external disturbances, two controllers give similar results. When there is an external disturbance, in the Figure 16b, it is seen that the terminal sliding mode controller generates a small amount of chattering. However, it is seen that the fuzzy sliding mode controller doesn't cause any problems.



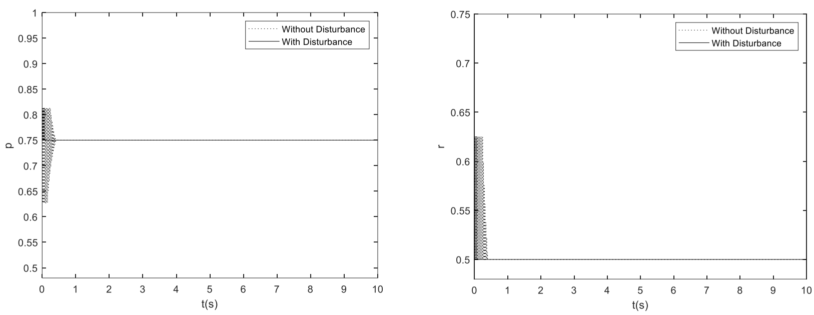
(a) (b)

Figure 16

Tip deflection w with control parameters λ=diag (10 10), K=diag(10 10)

a) Without disturbances b) With a disturbance torque

Figure 17 shows the change of control parameters p and r over time. These control parameters are determined using the fuzzy logic controller. The control parameter p is updated between 0.5 and 1 (Fig. 17a), and the r control parameter is updated between 0 and 1. (Fig. 17b) For both control parameters, it is understood that the controller updates the control parameters rapidly within external disturbances.



(a) (b)

Figure 17

Control parameter ‘p’ over time - Control parameter ‘r’ over time λ=diag (10 10), K=diag (10 10)

Conclusions

This study aimed to decrease the trajectory tracking error of the system, through the development of a fuzzy terminal sliding mode controller. The Fuzzy-terminal Sliding Mode Controller is design to control a one link flexible manipulator. The innovation in this study, is the determination of the most appropriate control parameters in the terminal sliding mode controller, by using a fuzzy controller in order to reduce tracking error. For this, a Fuzzy Logic Controller has been designed in this study. Input and output parameters, control rule and limits in fuzzy logic control law, are developed by a trial and error method. The stability of this controller is guaranteed by the Lyapunov function. The proposed controller is applied to a flexible link manipulator, with and without external disturbances.

When the results are examined for two trajectories, it is seen that the fuzzy-terminal sliding mode controller is effective. In addition, it is considered, that the proposed controller is effective following the trajectory, with a very small error, even if it has an external disturbance within the system. This shows the controller's robustness potential. The purpose of this study is to update the control parameters in the terminal sliding mode control law, with a fuzzy logic control method. From the results, it is seen, that the developed controller, is more effective than the terminal sliding mode controller. For this model, the most appropriate results are presented, according to the control law, obtained by the trial and error method. As a result of the study, it was understood that the controller is valid.

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