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로봇 매니퓰레이터의 추적 제어를 위한 퍼지 적응 슬라이딩 모드 제어기

A Fuzzy Adaptive Sliding Mode Controller for Tracking Control of Robotic Manipulators

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Abstract: This paper describes the design of a fuzzy adaptive sliding mode controller for tracking control of robotic manipulators. The proposed controller incorporates a modified traditional sliding mode controller to drive the system state to a sliding surface and then keep the system state on this surface, and a fuzzy logic controller to accelerate the reaching phase. The stability of the control system is ensured by using Lyapunov theory. To verify the effectiveness of the proposed controller, computer simulation is conducted for a five-bar planar robotic manipulator. The simulation results show that the proposed controller can improve the reaching time and eliminate chattering of the control system at the same time.

Keywords: adaptive, fuzzy, sliding mode control, tracking control, robotic manipulator

I. INTRODUCTION

Robotic manipulators play important roles in industrial automation systems [1,2]. Especially, they are best suited to work in hazardous environments where human cannot. Tracking control of robotic manipulators is one of the challenging tasks due to the highly coupled and highly time-varying dynamic system. In addition, there always exist uncertainties in the system model such as parameter uncertainty and external disturbance which cause unstable performance of the control system. Therefore, there is a need to introduce tracking control strategies for robotic manipulators with robustness, adaptive capability, fast convergence and simple structure.

SMC (Sliding Mode Control) is a special class of robust variable structure controllers. SMC has gained much attention for its independence from parametric uncertainties and external disturbances under matching conditions. In general, a SMC law is designed such that the state trajectories of the closed-loop system are driven toward a specified sliding surface, and once on the sliding surface they slide towards the origin [3-5]. Usually, the conventional SMC uses a large switching gain formula for handling the uncertainties and external disturbances. However, the large value of switching gains will lead to a large dither of control signal and increase the chattering of the system. For eliminating the chattering, several methods based on the use of a boundary layer in the sliding mode have been reported [6-8]. Although these approaches can eliminate chattering, they degrade the robustness of control system. In [9], the continuous sliding mode control strategy was proposed which can drive the system state to a chattering free sliding mode but tends to produce conservative designs. In general, there is a trade-off between the smooth of the control input history and the tracking error of the SMC controller.

Fuzzy control systems, as a tool against the problem of uncertainty and vagueness, incorporate human experience into the task of controlling a plant. Recently, several researchers have tried to eliminate or attenuate the chattering by applying fuzzy theory. In [10,11], a combination of fuzzy logic tuning scheme and sliding mode control is presented for accelerating the reaching phase and reducing the influence of unmodelled uncertainties. However, the control scheme in [10,11] was proposed to apply just to linear control systems. In [12,13], the fuzzy sliding mode control approaches were presented in which the fuzzy control is used to properly adjust the feedback gain in the conventional sliding mode control system. As a result, alleviation of chattering and robust performance can be achieved. In other approaches, the fuzzy control is used to reconstruct the dynamic model of robotic manipulator or the control system while the sliding mode control is used to assign the fuzzy control rules initially and provide the global stability of the closed-loop system [14-17]. However, the main problem existing in the above approaches is the large number of fuzzy rules for the large dimension of the control systems.

In this paper, a proposed controller based on fuzzy control and adaptive sliding mode control is presented for tracking control of robotic manipulators. The proposed controller incorporates a modified traditional sliding mode controller to drive the system state to a sliding surface and then keep the system state on this surface, and a fuzzy logic controller to accelerate the reaching phase and to reduce the chattering in the sliding phase. The stability of the control system is ensured by using Lyapunov theory.

The rest of the paper is organized as follows. In Section II, the dynamic model of general robotic manipulator is presented in the presence of structured and unstructured uncertainties, and a traditional sliding mode control is designed. In Section III, the

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proposed fuzzy adaptive sliding mode controller is presented and the stability of the closed-loop system is proven. A five-bar planar robotic manipulator with planned trajectories is simulated to verify the validity of the proposed controller as given in Section IV. Finally, a conclusion is reached in Section V.

II. TRADITIONAL SLIDING MODE CONTROL FOR ROBOTIC MANIPULATORS

1. Dynamic model of robotic manipulators

The dynamic model of an *n*-link robotic manipulator is expressed by the following equation:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau} \quad (1)$$

where $\boldsymbol{q} = [q_1,...,q_n]^T$ is an $n \times 1$ vector of joint angular position; $\dot{\boldsymbol{q}} = [\dot{q}_1,...,\dot{q}_n]^T$ is an $n \times 1$ vector of joint velocity; $\ddot{\boldsymbol{q}} = [\ddot{q}_1,..., \ddot{q}_n]^T$ s an $n \times 1$ vector of joint acceleration; $\boldsymbol{\tau}$ is an $n \times 1$ vector of applied joint torques (control inputs); $\boldsymbol{M}(\boldsymbol{q})$ is an $n \times n$ inertia matrix; $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is an $n \times n$ matrix of Coriolis and centrifugal forces; and $\boldsymbol{G}(\boldsymbol{q})$ is an $n \times 1$ gravity vector.

The inertia matrix $\boldsymbol{M}(\boldsymbol{q})$ is symmetric and positive definite. It is also bounded as a function of $\boldsymbol{q}: \mu_1\boldsymbol{I} \le \boldsymbol{M}(\boldsymbol{q}) \le \mu_2\boldsymbol{I}$, $m_1 \le \|\boldsymbol{M}(\boldsymbol{q})\| \le m_2$. The matrix described by $\dot{\boldsymbol{M}}(\boldsymbol{q}) - 2\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is a skew symmetric matrix, that is $\boldsymbol{x}^T[\dot{\boldsymbol{M}}(\boldsymbol{q}) - 2\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})]\boldsymbol{x} = 0$ where $\boldsymbol{x}$ is an $n\times1$ nonzero vector. The gravity vector $\boldsymbol{G}(\boldsymbol{q})$ is bounded as a function of $\boldsymbol{q}: \boldsymbol{G}(\boldsymbol{q}) \le g_b$ where g_b is a function of $\boldsymbol{q}$. For simplification, $\boldsymbol{M}(\boldsymbol{q})$, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ and $\boldsymbol{G}(\boldsymbol{q})$ are written as $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{G}$, respectively.

If there is the presence of uncertainties in the system, M, C and G are only partly known. Thus, M, C and G can be described as follows:

$$\boldsymbol{M} = \hat{\boldsymbol{M}} + \Delta\boldsymbol{M} \quad (2)$$

$$\boldsymbol{C} = \hat{\boldsymbol{C}} + \Delta\boldsymbol{C} \quad (3)$$

$$\boldsymbol{G} = \hat{\boldsymbol{G}} + \Delta\boldsymbol{G} \quad (4)$$

where $\hat{\boldsymbol{M}}$, $\hat{\boldsymbol{C}}$ and $\hat{\boldsymbol{G}}$ are known parts of the estimated parameter, and ΔM, ΔC and ΔG are the unknown parts.

Therefore, in the presence of uncertainties, the dynamic model of robotic manipulators can be written as follows:

$$\hat{\boldsymbol{M}}\ddot{\boldsymbol{q}} + \hat{\boldsymbol{C}}\dot{\boldsymbol{q}} + \hat{\boldsymbol{G}} + \Delta\boldsymbol{\tau} = \boldsymbol{\tau} \quad (5)$$

where $\Delta\boldsymbol{\tau} = \Delta\boldsymbol{M}\ddot{\boldsymbol{q}} + \Delta\boldsymbol{C}\dot{\boldsymbol{q}} + \Delta\boldsymbol{G}$ is the vector of uncertainties of the robotic system.

2. Traditional sliding mode controller

Let $\boldsymbol{q}_d \in \mathbf{R}^n$ be the vector of desired state vector, and $\boldsymbol{e} = \boldsymbol{q} - \boldsymbol{q}_d$ the tracking error vector of the robotic manipulator. The first step in the design of sliding mode control is to define the sliding surface function as:

$$\boldsymbol{s} = \dot{\boldsymbol{e}} + \Lambda\boldsymbol{e} = \dot{\boldsymbol{q}} - \dot{\boldsymbol{q}}_r \quad (6)$$

where Λ is diagonal positive constant vector which determines the motion feature in the sliding surface; and the reference states are defined as:

$$\dot{\boldsymbol{q}}_r = \dot{\boldsymbol{q}} - \boldsymbol{s} = \dot{\boldsymbol{q}}_d - \Lambda\boldsymbol{e} \quad (7)$$

$$\ddot{\boldsymbol{q}}_r = \ddot{\boldsymbol{q}} - \dot{\boldsymbol{s}} = \ddot{\boldsymbol{q}}_d - \Lambda\dot{\boldsymbol{e}} \quad (8)$$

In the second step, a control law is designed as the following equation:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{eq} + \boldsymbol{\tau}_{sw} \quad (9)$$

where the first term τ_{eq} is the equivalent control which keeps the trajectory of the system state on sliding surface; and the second term τ_{sw} is the switching control which drives the system state toward the sliding surface when it is deviated from this surface.

The equivalent control is considered for the nominal system and can be obtained as:

$$\boldsymbol{\tau}_{eq} = \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_r + \hat{\boldsymbol{C}}\dot{\boldsymbol{q}} + \hat{\boldsymbol{G}} \quad (10)$$

The switching control is designed as:

$$\boldsymbol{\tau}_{sw} = -\hat{\boldsymbol{C}}\boldsymbol{s} - \boldsymbol{K}sign(\boldsymbol{s}) \quad (11)$$

where $\boldsymbol{K} = diag[K_1,...,K_n]$ is a diagonal positive definite matrix of switching gains; *sign*(s) is the signum function of the sliding surface.

Now, by substituting (6), (10) and (11) into (9) we obtain the traditional SMC for robotic manipulators:

$$\boldsymbol{\tau} = \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_r + \hat{\boldsymbol{C}}\dot{\boldsymbol{q}}_r + \hat{\boldsymbol{G}} - \boldsymbol{K}sign(\boldsymbol{s}) \quad (12)$$

Theorem 1: Consider the robotic manipulators which are described by dynamic model (5). If the sliding mode controller is designed by (11) in which the switching gain matrix $\boldsymbol{K}$ satisfies:

$$K_i \ge |\Delta\tau_i|_{bound}, \quad i = 1, ..., \mathrm{n} \quad (13)$$

where $|\Delta\tau_i|_{bound}$ is the boundary of Δτ, then the overall system is asymptotically stable.

Proof: Let us define the positive definite Lyapunov function candidate as:

$$V = \frac{1}{2}\boldsymbol{s}^T\hat{\boldsymbol{M}}\boldsymbol{s} \quad (14)$$

The derivative of V is:

$$\dot{V} = \frac{1}{2}(\dot{\boldsymbol{s}}^T\hat{\boldsymbol{M}}\boldsymbol{s} + \boldsymbol{s}^T\dot{\hat{\boldsymbol{M}}}\boldsymbol{s} + \boldsymbol{s}^T\hat{\boldsymbol{M}}\dot{\boldsymbol{s}}^T) \quad (15)$$

From properties of dynamic model of robotic manipulators in Section II.1, we have:

$$\dot{\boldsymbol{s}}^T\hat{\boldsymbol{M}}\boldsymbol{s} = \boldsymbol{s}^T\hat{\boldsymbol{M}}\dot{\boldsymbol{s}}^T \quad (16)$$

$$\boldsymbol{s}^T[\dot{\hat{\boldsymbol{M}}} - 2\hat{\boldsymbol{C}}]\boldsymbol{s} = 0 \quad \text{or} \quad \boldsymbol{s}^T\dot{\hat{\boldsymbol{M}}}\boldsymbol{s} = 2\boldsymbol{s}^T\hat{\boldsymbol{C}}\boldsymbol{s} \quad (17)$$

Substituting (16) and (17) into (15) yields:

$$\begin{aligned}\dot{V} &= \boldsymbol{s}^T[\hat{\boldsymbol{C}}\boldsymbol{s} + \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}} - \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_r] \\ &= \boldsymbol{s}^T[\hat{\boldsymbol{C}}\boldsymbol{s} + \boldsymbol{\tau} - \hat{\boldsymbol{C}}\dot{\boldsymbol{q}} - \hat{\boldsymbol{G}} - \Delta\boldsymbol{\tau} - \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_r]\end{aligned} \quad (18)$$

Now, substituting control input from controller (12) into (18) we obtain:

$$\dot{V} = \boldsymbol{s}^T\left[-\boldsymbol{K}sign(\boldsymbol{s}) - \Delta\boldsymbol{\tau}\right]$$
$$= \sum_{i=1}^{n}\left(-K_i|s_i| - \Delta\tau_i s_i\right) \le \sum_{i=1}^{n}|s_i|\left(-K_i + |\Delta\tau_i|\right) \quad (19)$$

By choosing the switching gains K_i (i = 1,..,n) satisfying (11) we have:

$$\dot{V} \le 0 \quad (20)$$

From (14) and (20), it could be concluded that the overall system is asymptotically stable.

III. PROPOSED FUZZY ADAPTIVE SLIDING MODE CONTROLLER

The traditional SMC introduced in Section II involves two phases: reaching phase and sliding phase. In the designing of SMC, if a large switching gain $\boldsymbol{K}$ of switching control is chosen, the reaching phase will be accelerated. However, this large switching gain will cause big chattering in the sliding phase. On the other hand, with a small switching gain, the chattering in the sliding phase will be reduced, but the reaching phase is slow. Thus, an additional controller τ_F is introduced as a solution to this problem.

The auxiliary fuzzy controller is proposed as follows:

$$\boldsymbol{\tau}_F = -\boldsymbol{K}_F\boldsymbol{s} \quad (21)$$

where $\boldsymbol{K}_F$ = diag[K_{F1},...,K_{Fn}] is a positive diagonal matrix defined as follows.

The components K_{Fi} of the matrix $\boldsymbol{K}_F$ are continuously adjusted by the use of fuzzy logic, depending on the change of sliding functions s_i (i=1,..,n). The purpose of the adjusting of components K_{Fi} is to have the following rule base:

1) If s_i is positive large, then τ_{Fi} is negative large;
2) If s_i is positive small, then τ_{Fi} is negative small;
3) If s_i is negative large, then τ_{Fi} is positive large;
4) If s_i is negative small, then τ_{Fi} is positive small.

Based on this reasoning, the following fuzzy rules are used for tuning K_{Fi}:

1) If $|s_i|$ is large, then γ_i is large.
2) If $|s_i|$ is small, then γ_i is small.

The fuzzy logic controller for tuning $\boldsymbol{K}_F$ is depicted in Fig. 1. Using fuzzy labels *large* and *small,* the following membership functions are defined for inputs of the fuzzy logic controller:

$$\mu_{s_i\_large} = 1 - \exp\left(-\frac{|s_i|}{\sigma_i}\right) \quad (22)$$

$$\mu_{s_i\_small} = \exp\left(-\frac{|s_i|}{\sigma_i}\right) \quad (23)$$

where σ_i (i = 1,...,n) are positive constants.

The membership functions for outputs K_{Fi} are defined as singletons:

$$\mu_{K_{Fi}\_large} = \begin{cases}1, & K_{Fi} = K_{Fmi}\\ 0, & K_{Fi} \ne K_{Fmi}\end{cases} \quad (24)$$

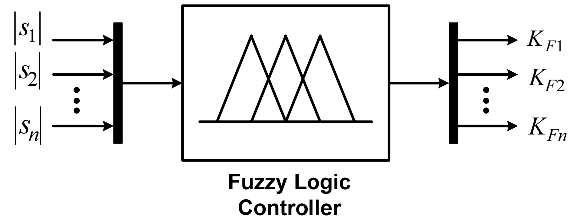

그림 1. K_F 튜닝을 위한 퍼지 논리 제어기.
Fig. 1. The fuzzy logic controller for tuning K_F.

$$\mu_{K_{Fi}\_small} = \begin{cases}1, & K_{Fi} = 0\\ 0, & K_{Fi} \ne 0\end{cases} \quad (25)$$

where K_{Fmi} are positive scaling factors (i = 1,..,n).

Using the max-min defuzzification method for the fuzzy schemes above yields [10]:

$$K_{Fi} = K_{Fmi}\left(1 - \exp(-\frac{|s_i|}{\sigma_i})\right) \quad (26)$$

where K_{Fmi} and σ_i are tuning parameters (i = 1,..,n).

In addition, the switching controller (11) is replaced by the following controller:

$$\boldsymbol{\tau}_s = -\hat{\boldsymbol{C}}\boldsymbol{s} - \boldsymbol{T}\boldsymbol{s} \quad (27)$$

where $\boldsymbol{T}$ is a diagonal positive matrix for enhancing the stability of the control system.

The proposed fuzzy adaptive sliding mode controller for robotic manipulators has the following form:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{eq} + \boldsymbol{\tau}_s + \boldsymbol{\tau}_F$$
$$= \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_{ar} + \hat{\boldsymbol{C}}\dot{\boldsymbol{q}}_{ar} + \hat{\boldsymbol{G}} - \boldsymbol{T}\boldsymbol{s} - \boldsymbol{K}_F\boldsymbol{s}. \quad (28)$$

Theorem 2: Consider the robotic manipulators described by dynamic model (5). If the proposed fuzzy adaptive sliding mode controller is designed by (28) in which the fuzzy logic controller τ_F is defined by (21), $\boldsymbol{K_F}$ is tuned by (26) and T_i (i=1,..,n) are chosen large enough, then the overall system is asymptotically stable.

Proof: Let us define the positive definite Lyapunov function candidate (11), and with the proposed control law (25) we have the first derivative $\dot{V}$:

$$\dot{V} = \boldsymbol{s}^T[\hat{\boldsymbol{C}}\boldsymbol{s} + \boldsymbol{\tau} - \hat{\boldsymbol{C}}\dot{\boldsymbol{q}} - \hat{\boldsymbol{G}} - \Delta\boldsymbol{\tau} - \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_r]$$
$$= \boldsymbol{s}^T\left[-\boldsymbol{T}\boldsymbol{s} - \Delta\boldsymbol{\tau} - \boldsymbol{K}_F\boldsymbol{s}\right]$$
$$= \sum_{i=1}^{n}\left(-T_i s_i^2 - \Delta\tau_i s_i\right) - \sum_{i=1}^{n}K_{Fi}s_i^2 \quad (29)$$
$$\le \sum_{i=1}^{n}\left(-T_i s_i^2 + |\Delta\tau_i||s_i|\right) - \sum_{i=1}^{n}K_{Fi}s_i^2$$

We assume that:

$$|\Delta\tau_i| \le \varsigma_i|s_i|, \quad i = 1,...,n \quad (30)$$

where ζ_i (i = 1,..., n) are positive constants which always can be found.

By substituting (30) and (26) into (29) we obtain:

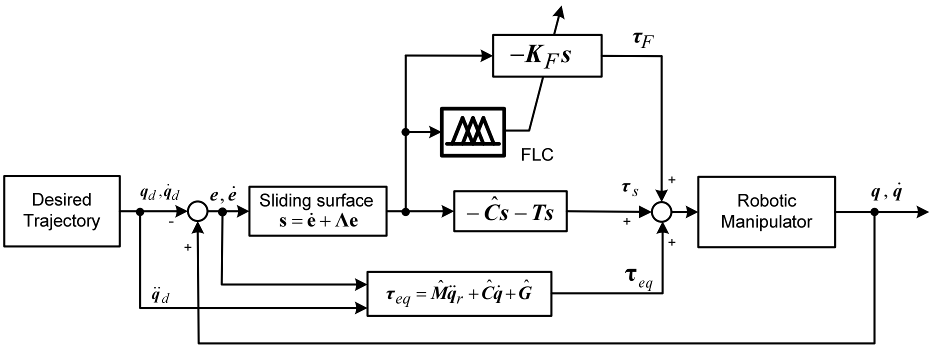

그림 2. 제안된 퍼지 적응 슬라이딩 모드 제어기의 블록 다이어그램.

Fig. 2. Block diagram of the proposed fuzzy adaptive sliding mode controller.

$$\dot{V} \le \sum_{i=1}^{n}\left(-T_i s_i^2 + \varsigma_i s_i^2\right) - \sum_{i=1}^{n} K_{Fmi}\left(1-\exp(-\frac{|s_i|}{\sigma_i})\right)s_i^2 \quad (31)$$

In addition, since K_{Fmi} is positive, we also have:

$$K_{Fmi}\left(1-\exp(-\frac{|s_i|}{\sigma_i})\right)s_i^2 \ge 0 \quad (32)$$

Therefore, if we choose $T_i \ge \zeta_i$, then $\dot{V} \le 0$. It could be concluded that the overall system is asymptotically stable based on Lyapunov theory.

It is important to note that the magnitude of the fuzzy controller (21) will increase with an increase of the sliding function manitude $|s_i|$ and vice versa. But the sign of the fuzzy control component is opposite to that of the sliding function component. The fuzzy controller (21) has an influence on the overall control action such that when the state trajectories are far from the sliding surface, the gain components K_{Fi} are increased to drive them to the sliding surface fast. And when the state trajectories approach the sliding surface, the components K_{Fi} are decreased. Tuning the coefficients σ_i depends on the magnitudes of the sliding functions, while the values K_{Fmi} depend on the saturation condition of the control input.

IV. EXAMPLE SIMULATION

The proposed controller is applied to the trajectory tracking control of a five-bar planar robotic manipulator which is described in Fig. 3. The robotic manipulator has 2 active joints, 3 passive joints and five links. The active joints are actuated by actuators while the passive joints are free to move.

The dynamic model of the robotic five-bar planar manipulator in the active joint space is expressed by the following equation [18]:

$$\boldsymbol{M}_a\ddot{\boldsymbol{q}}_a + \boldsymbol{C}_a\dot{\boldsymbol{q}}_a = \boldsymbol{\tau}_a \quad (33)$$

where $\boldsymbol{q}_a = [q_{a1}, q_{a2}]^T$ is a vector which represents two active joint angles. And $\dot{\boldsymbol{q}}_a = [\dot{q}_{a1}, \dot{q}_{a2}]^T$, $\ddot{\boldsymbol{q}}_a = [\ddot{q}_{a1}, \ddot{q}_{a2}]^T$ are velocity vector and acceleration vector, respectively. $\boldsymbol{M}_a$ is generalized inertia matrix, $\boldsymbol{C}_a$ is vector of Coriolis and centrifugal forces. And $\boldsymbol{\tau}_a = [\tau_{a1}, \tau_{a2}]^T$ is vector of the generalized torque of active joints A_1 and A_2. The dynamic model (33) has the properties as expressed in Section II.1.

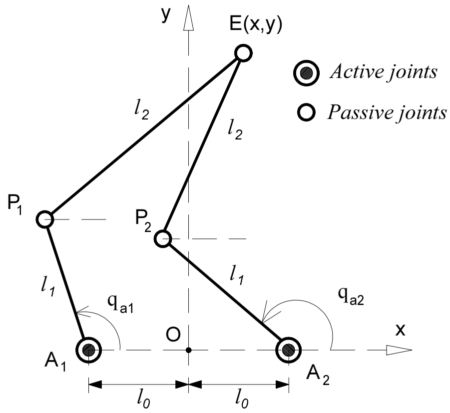

그림 3. 5-bar 평면 매니퓰레이터.

Fig. 3. The five-bar planar manipulator.

The link parameters of the five-bar manipulators are l_1= 0.102 m, l_2= 0.18 m, l_0= 0.066 m, m_1= 0.8 kg, m_2= 1.2 kg, I_{z1}= 0.0013 kgm^2, I_{z2}= 0.0027 kgm^2, l_{c1}= 0.055 m, l_{c2}= 0.091 m in which l_0, l_1, l_2 are the link lengths; m_1, m_2 are the masses; I_{zi1}, I_{zi2} are the inertias tensor of links of serial chain i; l_{c1}, l_{c2} are the distances from the joints to the center of mass for each link of the five-bar manipulator.

In practice, it is very difficult to measure the distances from the joint to the center of mass and the inertias tensor of links. So we conducted the simulations with different parameters both in mechanical model of robot and in the controllers as follows:

$$\hat{l}_{ci} = 0.9 l_{ci}, \quad i = 1,2 \quad (34)$$

where $\hat{l}_{ci}$ were used for calculating $\hat{\boldsymbol{M}}_a$, $\hat{\boldsymbol{C}}_a$ in the controllers. This treatment will make the modelling errors $\Delta\boldsymbol{M}_a$ and $\Delta\boldsymbol{C}_a$ of the dynamic model.

The traditional sliding mode controller (12) using BLM (Boundary Layer Method) (32) applied to the five-bar robotic manipulator is expressed as follows:

$$\boldsymbol{\tau}_a = \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_{ar} + \hat{\boldsymbol{C}}\dot{\boldsymbol{q}}_{ar} - \boldsymbol{K}sat(\boldsymbol{s}/\phi) \quad (35)$$

where $sat(\boldsymbol{s}/\phi)$ is saturation function defined by [3]:

$$sat(s/\phi) = \begin{cases} s/\phi & if\ |s| \le \phi \\ sign(s) & if\ |s| > \phi. \end{cases}$$

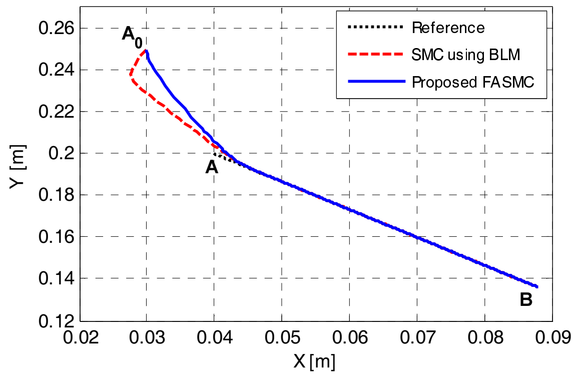

그림 4. 선형 궤적 추적 결과.

Fig. 4. Result of tracking linear trajectory.

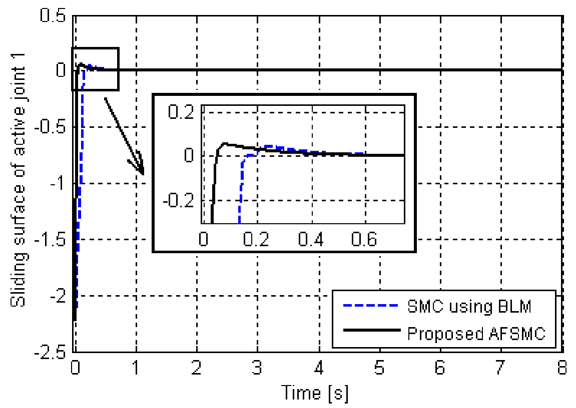

그림 5. 능동 관절 1 슬라이딩면.

Fig. 5. Sliding surface of active joint 1.

The proposed fuzzy adaptive sliding mode controller (FASMC) applied to the five-bar robotic manipulator is expressed as follows:

$$\boldsymbol{\tau}_a = \hat{\boldsymbol{M}}\ddot{\boldsymbol{q}}_{ar} + \hat{\boldsymbol{C}}\dot{\boldsymbol{q}}_{ar} - \boldsymbol{T}\boldsymbol{s} - \boldsymbol{K}_F\boldsymbol{s} \tag{36}$$

where $\boldsymbol{K}_F$ is tuned by (26).

Simulation studies were conducted on Matlab-Simulink and the mechanical of the five-bar planar manipulator was built on SimMechanics toolbox following the method presented in [19]. The simulations were carried out with respect to the case when the five-bar manipulator tracks a line on XY plane. The comparisons between the performance of the traditional SMC using BLM and the proposed FASMC were performed. For the linear reference trajectory, the starting point is **A**(0.04, 0.2) and the ending point is **B**(0.088, 0.136). The time for tracking is 8 seconds.

The parameters in the traditional SMC were set to be: $K_1 = K_2 = 0.6$, $\phi_1 = \phi_2 = 0.1$. The parameters in the proposed FASMC controller were set to be: $T_1 = T_2 = 0.6$, $\phi_1 = \phi_2 = 0.1$, $K_{Fm1} = K_{Fm2} = 2$, $\sigma_1 = \sigma_2 = 1/5$. These parameters were obtained by trial and error method.

Fig. 4 shows the results of tracking a linear trajectory. The initial point of the end-effector of the five-bar manipulator is $\mathbf{A_0}$(0.03, 0.25). It can be seen that the end-effector of robot can track the linear reference trajectory well.

The comparisons of the sliding surfaces of active joint 1 and active joint 2 are shown in Figs. 4 and 5. It can be seen that in the case of using FASMC, the system state reaches the sliding surface more quickly than the case of SMC using BLM. This better result of using FASMC is obtained by introducing the fuzzy control component.

Next, Figs. 7 and 8 show the control inputs of active joint 1 and active joint 2 in the case of SMC using BLM. The enlargements of localized regions show that the chattering phenomenon still happen in this case.

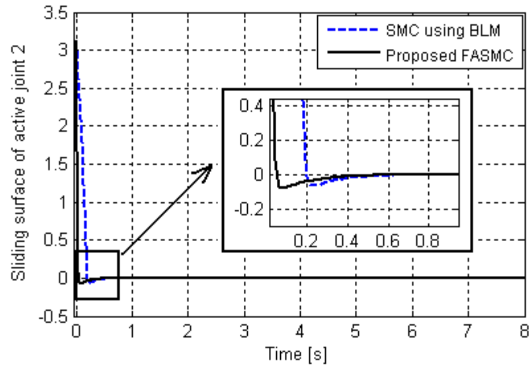

그림 6. 능동 관절 2 슬라이딩면.

Fig. 6. Sliding surface of active joint 2.

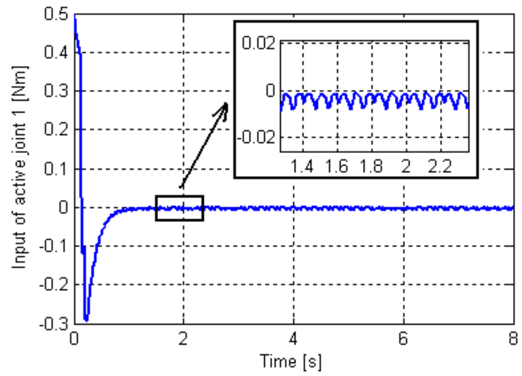

그림 7. BLM을 사용하는 SMC 경우, 능동 관절 1의 제어 입력.

Fig. 7. Control input of active joint 1 in the case of SMC using BLM.

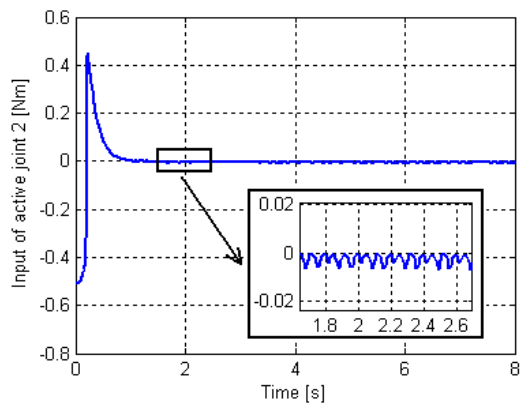

그림 8. BLM을 사용하는 SMC 경우, 능동 관절 2의 제어 입력.

Fig. 8. Control input of active joint 2 in the case of SMC using BLM.

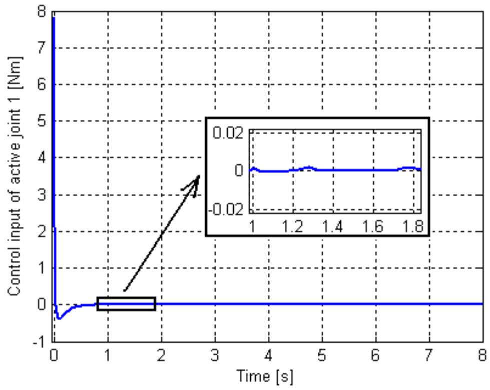

그림 9. 제안된 FASMC를 사용하는 경우, 능동 관절 1의 제어 입력.

Fig. 9. Control input of active joint 1 in the case of using proposed FASMC.

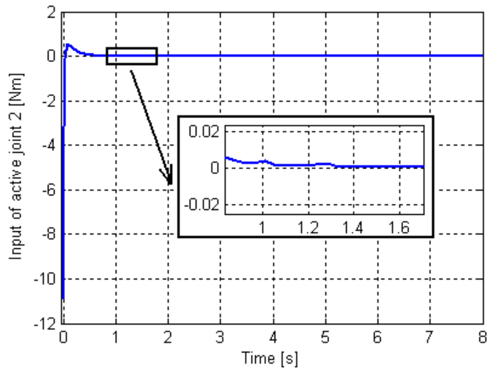

그림 10. 제안된 FASMC를 사용하는 경우, 능동 관절 2의 제어 입력.

Fig. 10. Control input of active joint 2 in the case of using proposed FASMC.

Figs. 9 & 10 show the control inputs of active joint 1 and active joint 2 in the case of using proposed FASMC. It can be seen from the enlargements of localized regions that the chattering phenomenon is eliminated in comparison with the case of SMC using BLM.

It could be concluded from the above-mentioned simulation results that the proposed fuzzy adaptive sliding mode controller is of high efficiency for the control of robotic manipulators.

V. CONCLUSION

A fuzzy adaptive sliding mode controller is proposed for tracking control of robotic manipulators. The novel controller is achieved by combining a modified traditional sliding mode controller and a fuzzy logic controller which has advantages such as flexibility and adaptation. The modified traditional sliding mode controller drives the system state to a sliding surface and then keeps the system state on this surface, while the fuzzy logic controller is used to accelerate the reaching phase and to reduce the chattering in the sliding phase. The stability of the control system is ensured by using Lyapunov theory. Simulations are conducted for a five-bar planar robotic manipulator. Compared with the traditional sliding mode control, the proposed controller brings about a shorter reaching time of system state to the sliding surface while eliminating the chattering phenomenon at the same time.

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