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An Adaptive Fuzzy Sliding Mode Control for Minimally Invasive Surgical Robot's Remote Center Mechanisms*

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Abstract - Being the most important component of minimally invasive surgical robot system, remote centre mechanisms (RCM) composed of three joints, achieve the position and orientation adjustment of the surgical instrument inside a patient's body. In order to implement the high-precision position control and eliminate the adverse effect result from the friction of RCM's joints, in this paper, a fuzzy sliding mode controller with the friction compensation is designed. The result of simulation and experiment show that the controller designed can provide a trajectory tracking with real-time, high-precision performance and strong robustness.

Index Terms - Minimally invasive surgical robot, Remote centre mechanisms, Friction compensation, Adaptive fuzzy sliding mode control.

I. INTRODUCTION

Minimally invasive surgical robot (MISR) used in performing minimally invasive surgical procedures can offer many benefits over traditional open surgery techniques, including less pain, shorter hospital stays, quicker return to normal activities, minimal scarring, reduced recovery time, and less injury to tissue. Consequently, demand for minimally invasive surgery using such as MISR is strong and growing.

MISR has a slave manipulator coupled to medical device adapted to hold and/or move the medical device for performing a medical procedure, and a control system for controlling movement of the joint according to user manipulation of a master manipulator. The slave manipulator systems achieve surgical process through seven degrees of freedom, which includes two parts: position adjustment mechanisms and remote centre mechanisms. The position adjustment mechanisms locate the incisions in the patient's body surface, which are made up of four passive joints, including the first, second, third and fourth joint. Remote centre mechanisms implement position and pose adjustment of surgical instruments within the patient's body, which composed of three active joints, including the fifth, sixth, seventh joint, wherein, the fifth joint is a rotary join, the sixth joint is a balance quadrilateral structure with three linkages, the seventh joint is a sliding translational joint. Remote center mechanisms is shown below.

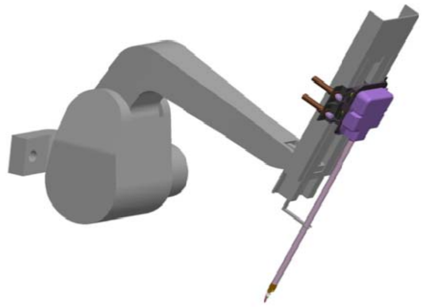

Fig.1 Remote center mechanisms.

Being the most important the composition structure of slave manipulator, slave manipulator perform any fine medical procedure ,such as surgical sutures, needles etc, are achieved by the precise movement of RCM. Due to each joint of RCM generally includes a drive motor, reducer, load rod, etc., there inevitably exist the joints flexible, non-linear effects of friction, load disturbance and backlash effect, etc. Since slave manipulator's motion trajectory tracking user manipulation of a master manipulator, the motion of RCM is also a low frequency (less than 3Hz) and low speed (rotational speed less than $\pi / 3s$, translational velocity less than 30mm/s), thereby, the coupling affect among the joints are enough small to negligible, meanwhile the friction of the joints have a significant impact on the motion precision.

There is a complicated phenomenon of friction in the joints of RCM, including rolling friction, sliding friction, etc. The friction associated with many factors, including joint speed, load torque, lubrication conditions, temperature, etc. Since the friction in the joints is one of the main factors that deteriote the performance of RCM's controller, the friction compensation can improve greatly trajectory tracking accuracy of RCM. Generally, joint friction compensation mode can be divided into two classes: friction compensation based mode and adaptive friction compensation[1-4]. For friction compensation based mode, it must establish a precise mathematical model of friction, but it is very difficult in practice. For the friction compensation mode based on adaptive system[5, 6], fuzzy system can obtain the real-time exact value of friction because fuzzy system can approximate any nonlinear accuracy of any continuous function with arbitrary precision[7, 8].

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Since RCM is in nature a time-varying, weakly coupled, highly nonlinear mechanical systems, then the high-precise motion of RCM will rely on a reliable high-performance control algorithm, such as the classic PID control, adaptive control [9], robust control[10, 11] and sliding mode control[12-14], and so forth. By comparing these algorithms above-mentioned, firstly, the controllable ability and anti-interference ability of the classic PID is too weak to meet the external environment changes, or very vulnerable to be influenced by system parameters changes. Secondly, Robust controller need to know the upper bound of perturbations from uncertainties, but in practice, it is impossible to know the exact the upper bounds of perturbations. Thirdly, based on mathematical model, classic adaptive controller need the online identification of the model parameters and parameters adjustment, accompanying with large amount of calculation, therefore, classic adaptive control is not suitable for high security and real-time control systems. Finally, sliding mode variable structure controller (SMC) is a special nonlinear control, with simple physical implementation, meanwhile without online identification system parameters. Due to SMC has nothing to do with design parameters and disturbances of plants, SMC can fast response to parameter variations without sensitive to all kinds of disturbances. For the strong robustness, the system can slide along the sliding surface by switching function, without parameter perturbation. Because uncontinuous switching characteristics in nature, SMC will cause the system "chattering", which easy to excite the unmodeled dynamic characteristics of the robot system, affect the control system performance, and increase the control of energy, or even damage the controller components. As can be seen, how to deal with "chattering" will exert an extremely strong influence on the performance of SMC. In summary, after examining various factors, this paper applies a Fuzzy Sliding Mode Variable Structure Control with friction compensation (FSMCC) [15, 16] to achieve real-time, high-precision and strong robustness trajectory tracking of RCM.

This paper is organized as follows: In Section 2, classic sliding mode controller is designed. In Section 3, an adaptive fuzzy sliding mode control with friction feed-forward compensation is designed to control RCM. In Section 4, simulation and experiment verify the effectiveness of the controller designed. This paper concludes in Section 5.

II. CLASSIC SLIDING MODE CONTROLLER DESIGN

A. RCM's Dynamic Model

Remote centre mechanisms mainly consist of three linkages which include servo motor, harmonic reducer, load link. The dynamic equation of three-link RCM is

$$(H(q)+\eta^2 * J_m)\ddot{q}+(C(q,\dot{q})+\eta^2 * B_m)\dot{q}+G(q)+F_v(q,\dot{q})+\tau_{ext}=\tau \quad (1)$$

where, $H(q), J_m, B_m, G(q), F_v(q,\dot{q}), \tau_{ext}, \tau, q, \dot{q}, \ddot{q}$ are all $n\times 1$ vector, η is reduction ratio of the harmonic reducer, $F_v(q,\dot{q})$ are coulomb friction and viscous friction, τ_{ext} is externally applied torque, τ is control input, $H(q)$ is inertial matrix, $C(q,\dot{q})$ is $n\times n$ matrix of Coriolis and centrifugal forces, $G(q)$ is gravity vector, $q, \dot{q}, \ddot{q}$ are position vector, velocity vector and acceleration vector of joint, respectively. For simplification, $(H(q)+\eta^2 * J_m)$ is written as M, $C(q,\dot{q})$ is written as C, $G(q)$ is written as G, $(\eta^2 B_m \dot{q} + F_v(q,\dot{q}) + \tau_{ext})$ is written as F_{dist}, Equation(1) can be rewritten as:

$$M\ddot{q}+C\dot{q}+G+F_{dist}=\tau \quad (2)$$

It is noticed that M, C, G are only partly known and therefore there exists uncertainty in the system model.

B. Classical Sliding Mode Control for RCM

Define the tracking error

$$e = q - q_d \quad (3)$$

where q is the joint position, q_d is joint desired position.

Define the sliding surface

$$s = \dot{e} + \lambda e \quad (4)$$

where $\lambda = diag[\lambda_1, \cdots, \lambda_n], \lambda_i > 0$

Define the reference state

$$\begin{aligned} \dot{q}_r &= \dot{q} - s = \dot{q}_d - \lambda e \\ \ddot{q}_r &= \ddot{q} - \dot{s} = \ddot{q}_d - \lambda \dot{e} \end{aligned} \quad (5)$$

Choose the control input τ

$$\begin{aligned} \tau &= \hat{\tau} - K\,\mathrm{sgn}(s) \\ \hat{\tau} &= \hat{M}\ddot{q}_r + \hat{C}q_r + \hat{G} - As \end{aligned} \quad (6)$$

where $\hat{M}, \hat{C}, \hat{G}$ are the estimations of M, C, G, respectively,

$$K = diag[K_{11}, \cdots, K_{ii}, \cdots, K_{nn}], \mathrm{K_{ii}} > 0$$
$$A = diag[a_1, \cdots, a_i, \cdots, a_n], a_i > 0$$

Putting (6) into (2) leads to

$$M\dot{s} + (C+A)s = \Delta f - K\,\mathrm{sgn}(s) \quad (7)$$

where

$$\Delta f = \Delta M\ddot{q}_r + \Delta C\dot{q}_r + \Delta G - F_{dist},$$
$$\Delta C = \hat{C} - C, \Delta G = \hat{G} - G, \Delta M = \hat{M} - M,$$

Assuming $|\Delta f_i| < |\Delta f_i|_{bound}$ where $|\Delta f_i|_{bound}$ is the boundary of $|\Delta f_i|$, choose K such that

$$K_{ii} \geq |\Delta f_i|_{bound} \quad (8)$$

To prove the stability of the system, choose the Lyapunov function candidate to be

$$V = \frac{1}{2}s^T Ms$$
$$\dot{V} = s^T[-(C+A)s + \Delta f - K\,\mathrm{sgn}(s) + Cs]$$
$$= \sum_{i=1}^{n}(s_i[\Delta f_i - K_{ii}\,\mathrm{sgn}(s_i)]) - s^T As$$

since M is symmetric and positive definite, then for $V > 0$, when $s \neq 0$

from (8)

$$\Delta f_i - K_{ii}\,\mathrm{sgn}(s_i) = \Delta f_i - K_{ii} \leq 0, \text{ when } s_i > 0$$
$$\Delta f_i - K_{ii}\,\mathrm{sgn}(s_i) = \Delta f_i - K_{ii} \geq 0, \text{ when } s_i < 0$$

so that

$$s_i[\Delta f_i - K_{ii}\,\mathrm{sgn}(s_i)] < 0$$

thus

$$\dot{V} = \sum_{i=1}^{n}(s_i[\Delta f_i - K_{ii}\,\mathrm{sgn}(s_i)]) - s^T As \leq -s^T As \leq 0$$

According to Lyapunov stability theorem, the system is stable, but there is no guarantee that $\lim_{t\to\infty} s = 0$. The chattering is caused by the constant value of K and the discontinuous sign function sgn(s). One way to eliminate the chattering is to replace sgn(s) by a saturation function sat(s). Saturation function sat(s) expression is as follows:

$$sat(s) = \begin{cases} 1 & s > \Delta \\ ks & |s| \leq \Delta, k = \dfrac{1}{\Delta} \\ -1 & s < -\Delta \end{cases} \quad (9)$$

where, the boundary layer thickness Δ determines the accuracy of controller. The smaller thickness, the higher the control precision, while the more serious buffeting. On the contrary, the smaller chattering, lower precision controller.

C. Simulation of the Classical Sliding Mode Control for RCM

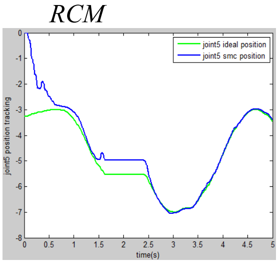

Fig.2 Position tracking of joint 5.

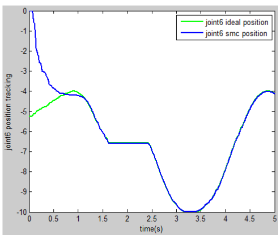

Fig.3 Position tracking of joint 6.

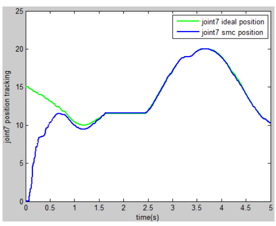

Fig.4 Position tracking of joint 7.

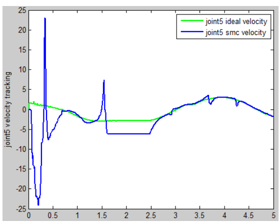

Fig.5 Velocity tracking of joint 5.

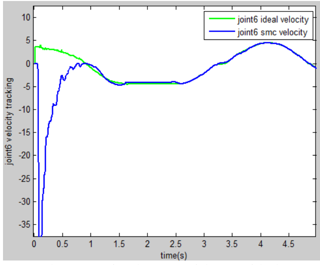

Fig.6 Velocity tracking of joint 6.

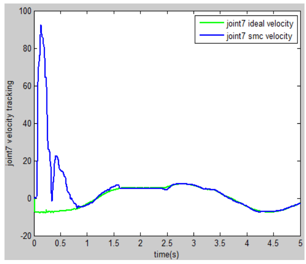

Fig.7 Velocity tracking of joint 7.

In the above figure, Fig.2, Fig.3, Fig.4 are position tracking curve of the joint 5, joint 6 and joint 7 of RCM, respectively, Fig.5, Fig.6, Fig.7 are velocity tracking curve of the joint 5, joint 6 and joint 7 of RCM, respectively. As can be seen all drawing above, the green line represents the ideal trajectory, the blue lines represent the trajectory tracking from SMC. According to the simulation results show that SMC have better position tracking performance in accuracy and smoothness, but it's velocity tracking performance is ordinary because there are some "chattering" on the velocity tracking curve.

III. DESIGN OF AN ADAPTIVE FUZZY SLIDING MODE CONTROL WITH FRICTION COMPENSATION

A. Classic adaptive fuzzy system design

When the membership function is Gaussian function, adaptive fuzzy system can approximate any nonlinear continuous function with arbitrary precision. Usually, a fuzzy system has one or more inputs and a single output. There are four basic parts in a fuzzy system. The fuzzification and defuzzification are the interface between the fuzzy systems and the crisp systems. The rule base includes a set of "if…then…" rules extracted from the human experience. Each rule describes a relation between the input space and the output space. For each rule, the inference engine maps the input fuzzy sets to an output fuzzy set according to the relation defined by the rule. It then combines the fuzzy sets from all the rules in the rule base into the output fuzzy set. This output fuzzy set is translated to a crisp value output by the defuzzification. The following figure shows the typical structure of the fuzzy system.

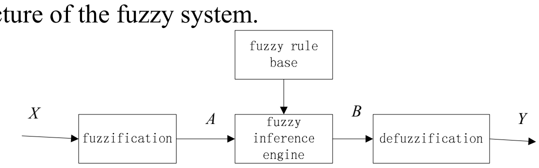

Fig.8 Diagram for a fuzzy system.

Generally, design of fuzzy systems by the following two steps:

1) Define Fuzzy Sets and Membership Function

Define m_i fuzzy sets $A_i^{l_i}(l = 1, 2, \cdots, m_i)$ for variable $x_i(i = 1, 2, \cdots, n)$.

And the membership functions of fuzzy set $A_i^{l_i}$ can be written as

$$u_{A_i}^{l_i}(x_i)=\exp[-(\frac{x_i-\overline{x}_i^{l_i}}{\sigma})^2]$$

where $\overline{x}_i^{l_i},\sigma$ is the centre and width of the membership function, respectively.

2) Define Fuzzy Rules to Construct Fuzzy System

Define $\prod_{i=1}^{n} m_i$ fuzzy rules to construct a fuzzy system $u_D(x\,|\,\theta)$.

$$\begin{aligned}&\textit{if } x_1 \textit{ is } A_i^{l_1} \textit{ and} \cdots x_n \textit{ is } A_i^{l_n}, \textit{then } u_D \textit{ is } S^{l_1\cdots l_n},\\ &\text{where } l_1=1,2,\cdots,m_i, i=1,2,\cdots,n\end{aligned} \tag{10}$$

By choosing singleton fuzzification, center average defuzzification, Mamdani implication in the rule base and product inference engine, the output of the fuzzy system can be written as

$$u_D(x\,|\,\theta)=\frac{\sum_{l_1=1}^{m_1}\cdots\sum_{l_n=1}^{m_n}\overline{y}_u^{l_1\cdots l_n}(\prod_{i=1}^{n}u_{A_i}^{l_i}(x_i))}{\sum_{l_1=1}^{m_1}\cdots\sum_{l_n=1}^{m_n}(\prod_{i=1}^{n}u_{A_i}^{l_i}(x_i))}=\theta^T\xi(x)$$

where $\overline{y}_u^{l_1\cdots l_n}\in\theta\in R^{\prod_{i=1}^{n}m_i}$ is a free parameters, $\xi(x)$ is a $\prod_{i=1}^{n}m_i$ dimensional vector,it's the $l_1\cdots l_n$ element can be written *as*

$$\xi_{l_1\cdots l_n}(x)=\frac{\prod_{i=1}^{n}u_{A_i}^{l_i}(x_i)}{\sum_{l_1=1}^{m_1}\cdots\sum_{l_n=1}^{m_n}(\prod_{i=1}^{n}u_{A_i}^{l_i}(x_i))}$$

B. Fuzzy System Estimates the Friction of RCM's Joints

Fuzzy control rules expression(10) embeds the fuzzy controller by setting the initial parameters. Since the joint friction of RCM mainly distribute on the front two joints, meanwhile each joint velocity and frequency are relatively low, as well as the joints of RCM exerted on external torque are relatively small, in order to reduce calculation and improve the real-time control performance, only the friction of the joint 5, 6 are consider for compensation.

1) Define Fuzzy Sets and Membership Function

Joint velocity set $\dot{q}$ generate fuzzy sets $A_i(i=1,\cdots,5)$ by fuzzification, A_i are denoted as NB,NS,ZO,PS,PB. Fuzzy system is designed to be as:

$$\hat{F}(\dot{q}|\Theta)=\begin{bmatrix}\hat{F}_1(\dot{q}_1\,|\,\Theta_1)\\ \hat{F}_2(\dot{q}_2\,|\,\Theta_2)\end{bmatrix}=\begin{bmatrix}\Theta_1^T\xi^{l_1}(\dot{q}_1)\\ \Theta_2^T\xi^{l_2}(\dot{q}_2)\end{bmatrix}$$

Adaptive control law is designed to be as:

$$\dot{\Theta}_i=-\Gamma_i^{-1}s_i\xi^{l_i}(\dot{q}),\quad i=1,2,\ \ l_1=1,\cdots,5,\ \ \Gamma_i>0 \tag{11}$$

$$\xi^{l_i}(\dot{q})=\frac{\prod_{i=1}^{5}\mu_{A_i}^{l_i}(\dot{q}_i)}{\sum_{l_i=1}^{5}\prod_{i=1}^{5}\mu_{A_i}^{l_i}(\dot{q}_i)},\quad i=1,2,\ \ l_i=1,\cdots,5$$

where s_i is a value of *the ith sliding surface,* $\dot{q}$ *is joint velocity.*

2) Define Fuzzy Rules to Construct Fuzzy System

The fuzzy rule between the input $\dot{q}$ and output $\hat{F}(\dot{q}|\Theta)$ can be decided as follows:

If ($\dot{q}$ is NB) then ($\hat{F}(\dot{q}|\Theta)$ is NB)
If ($\dot{q}$ is NS) then ($\hat{F}(\dot{q}|\Theta)$ is NS)
If ($\dot{q}$ is ZO) then ($\hat{F}(\dot{q}|\Theta)$ is ZO)
If ($\dot{q}$ is PS) then ($\hat{F}(\dot{q}|\Theta)$ is PS)
If ($\dot{q}$ is PB) then ($\hat{F}(\dot{q}|\Theta)$ is PB)

Since the joint motion frequency less than 3Hz, joint velocity $\dot{q}_i\in[-\pi/6\quad \pi/6],\ i=1,2$.

If let $x=\dot{q}, x_i=\dot{q}_i$, then membership functions of A_i as follow:

$$\mu_{A_i}^{l_i}(\dot{q}_i)=\exp(-(\frac{x_i-\overline{x}_i^{l_i}}{\pi/2})^2)$$

where, $\overline{x}_i^{l_i}$ is $-\pi/6,-\pi/12,0,\pi/12,\pi/6$

Define fuzzy approximation error

$$f=\begin{bmatrix}f_1\\ f_2\end{bmatrix}=F(q\,|\,\Theta)-F(q\,|\,\Theta^*)$$

where Θ, Θ^* are actual parameters and ideal parameters of the adaptive control law, respectively.

C. An Adaptive Fuzzy Sliding Mode Control with Friction Compensation for RCM.

Let the control gain of expression (6) $K\,\mathrm{sgn}(s)$ is replaced by a fuzzy gain $\hat{F}_i(\dot{q}_i\,|\,\Theta_i)$, the new control input is then written as

$$\tau=\hat{M}(q)\ddot{q}_r+\hat{C}(q,\dot{q})\dot{q}_r+\hat{G}(q_d)-\hat{F}(\dot{q}|\Theta)-As$$

In order to eliminate the effect of approximation error and ensure system stability, the control law should include a robust item. the control law can be *written as*

$$\begin{aligned}&\tau=\hat{\tau}-\hat{F}(\dot{q}\,|\,\Theta)\\ &\hat{\tau}=\hat{M}(q)\ddot{q}_r+\hat{C}(q,\dot{q})q_r+\hat{G}(q_d)-As-W\,\mathrm{sgn}(s)\end{aligned} \tag{12}$$

where $W=\mathrm{diag}[w_1\quad w_2],\ w_i\ge|f_i|,\ i=1,2$

C. Control System Stability Proof

Define Lyapunov function as

$$V=\frac{1}{2}(s^TMs+\sum_{i=1}^{2}\tilde{\Theta}_i^T\Gamma_i\tilde{\Theta}_i),\ \ \tilde{\Theta}_i=\Theta_i^*-\Theta_i$$

$$
\begin{aligned}
\dot{V} &= s^T M\dot{s} + \frac{1}{2}s^T \dot{M}s + \sum_{i=1}^{2}\tilde{\Theta}_i^T\Gamma_i\dot{\tilde{\Theta}}_i \\
&= -s^T(-\tau + C\dot{q} + G + F_{dist} + M\ddot{q}_r - Cs) + \sum_{i=1}^{2}\tilde{\Theta}_i^T\Gamma_i\dot{\tilde{\Theta}}_i \qquad (13)\\
&= -s^T(M\ddot{q}_r + C\dot{q}_r + G + F_{dist} - \tau) + \sum_{i=1}^{2}\tilde{\Theta}_i^T\Gamma_i\dot{\tilde{\Theta}}_i
\end{aligned}
$$

where $\tilde{\Theta}_i, \Theta_i^*, \Theta_i$ are parameters error, ideal parameters and actual parameters of adaptive law, respectively.

Putting (12) into (13) leads to

$$
\begin{aligned}
\dot{V} &= -s^T(F(\dot{q}) - \hat{F}(\dot{q}\,|\,\Theta) + As + W\,\mathrm{sgn}(s)) + \sum_{i=1}^{2}\tilde{\Theta}_i^T\Gamma_i\dot{\tilde{\Theta}}_i \\
&= -s^T(F(\dot{q}\,|\,\Theta) - \hat{F}(\dot{q}\,|\,\Theta) + \hat{F}(\dot{q}\,|\,\Theta^*) - \hat{F}(\dot{q}\,|\,\Theta^*) + As + W\,\mathrm{sgn}(s)) + \sum_{i=1}^{2}\tilde{\Theta}_i^T\Gamma_i\dot{\tilde{\Theta}}_i \\
&= -s^T(\tilde{\Theta}^T\xi(\dot{q}) + \mathrm{f} + \mathrm{As} + W\,\mathrm{sgn}(s)) + \sum_{i=1}^{2}\tilde{\Theta}_i^T\Gamma_i\dot{\tilde{\Theta}}_i \\
&= -s^T\,\mathrm{As} - s^T f - W\,\mathrm{sgn}(s) + \sum_{i=1}^{2}(\tilde{\Theta}_i^T\Gamma_i\dot{\tilde{\Theta}}_i - s_i\tilde{\Theta}_i^T\xi(\dot{q}))
\end{aligned}
$$

where $\tilde{\Theta} = \Theta^* - \Theta$, $\mathrm{f} = \mathrm{F}(\dot{q}) - \hat{\mathrm{F}}(\dot{q}|\Theta^*)$, $\xi(\dot{q})$ is a fuzzy system

Putting (11) into (13) leads to

$$\dot{V} = -s^T\,\mathrm{As} - s^T f \text{-Wsgn(s)}$$

For $W = \mathrm{diag}[w_1 \quad w_2],\ w_i \ge |f_i|,\ i = 1,2$

Then $\dot{V} \le 0$,that is, system is stability.

IV. SIMULATION AND EXPERIMENT

A. Datum of Simulation and Experiment

1)In order to test friction compensation, assuming joint friction (Coulomb + viscous friction model) as

$$\begin{bmatrix} F_{v1} \\ F_{v2} \end{bmatrix} = \begin{bmatrix} 15q_1 + 6\,\mathrm{sgn}(q_1) \\ 15q_2 + 6\,\mathrm{sgn}(q_2) \end{bmatrix}$$

2) gravity vector as

$$\overline{g} = [\text{-}\cos(\mathrm{pi}/6) \quad 0 \quad \sin(\mathrm{pi}/6)]*9.8$$

3) Part of the Kinetic Parameters of RCM

TABLE I

THE KINETIC PARAMETERS OF RCM

joint	θ_i	d_i/mm	l_i/mm	α_i	m_i/kg	J_m	η
1	θ_5	971.5	0	$-\pi/2$	3.0339	7.87e-6	350
2	θ_6	0	0	$\pi/2$	2.9139	3.33e-6	370
3	0	d_7	0	0	0.6684	1.38e-6	132

4) Part of the controller parameters

TABLE II

THE CONTROL PARAMETERS OF FSMCC

λ	A	W	Γ_i
diag(10,10,10)	diag(20,20,20)	diag(1.5,1.5,1.5)	0.0001

B. Analysis of simulation and experiment

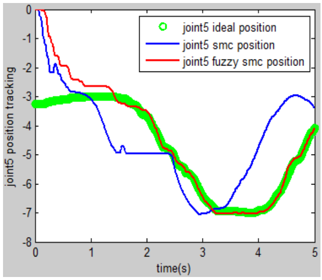

Fig.9 Position tracking of joint 5.

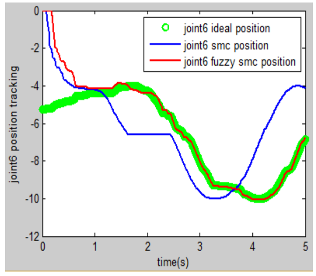

Fig.10 Position tracking of joint 6.

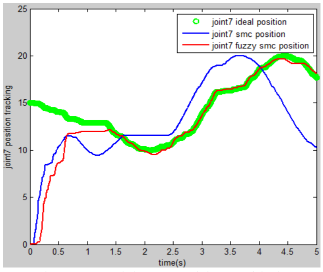

Fig.11 Position tracking of joint 7.

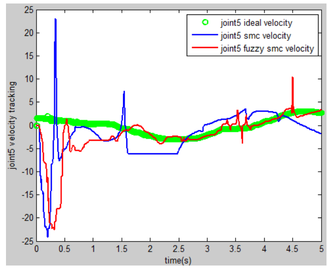

Fig.12 Velocity tracking of joint 5.

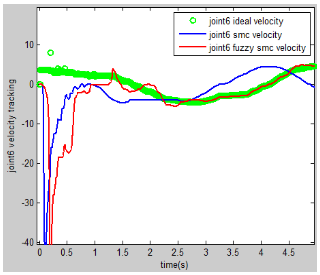

Fig.13 Velocity tracking of joint 6.

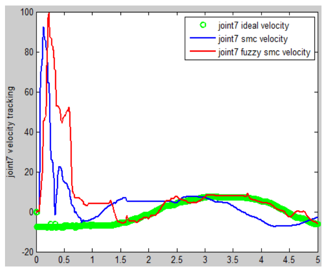

Fig.14 Velocity tracking of joint 7.

In the above figure, Fig.9, Fig.10, Fig.11 are position tracking curve of joint 5, joint 6 and joint 7, respectively. Fig.12, Fig.13, Fig.14 are velocity tracking curve of joint 5, jont 6, joint 7, respectively. As can be seen all drawing above, the green line represents the ideal trajectory, the red line represents the trajectory tracking generated from FSMCC, the blue lines represent the trajectory tracking from SMC. According to the simulation results above show that FSMCC have better position and velocity tracking performance than SMC in accuracy, smoothness, real time and robustness.

V. CONCLUSIONS

Due to the controller designed is based on the sliding mode control, the system inevitably exist small chattering, In addition, the initial parameters value of controller need to estimate roughly the upper bound of perturbations suffered from uncertainty. If initial parameters value of controller are far from actual perturbations suffered from uncertainty, the controller performance will be significantly deteriorated.

Fortunately, the friction compensation with adaptive fuzzy, to some extent, alleviate the difficulty in determining the initial control parameters, but need to be online to calculate membership function and update adaptive parameters, which bring some calculation cost. But since the joint number of RCM is relatively small, the calculation cost can be negligible basically.

Summary, both the theoretical studies and the simulation results demonstrate that controller designed in this paper can provide high-precision, strong robust and real-time tracking performance.

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