Robust Adaptive Fuzzy Sliding Mode Synchronous Control for a Planar Redundantly Actuated Parallel Manipulator

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Abstract—**Redundantly actuated parallel mechanisms could modify the deficiency of full parallel mechanisms. To achieve better trajectory tracking, a new sliding mode synchronous control with fuzzy inference mechanism is proposed. Based on Kane equation, a planar 2-DOF redundantly actuated parallel mechanism's dynamics model is formulated and detailed. With trajectory contour error, the synchronization error is defined and the sliding surface is determined. For parameters in switching surface, a fuzzy inference mechanism is used to find optimal values. After dynamic equation linearization, a robust adaptive fuzzy sliding mode synchronous controller is designed with a stability analysis. Matlab simulation results show that the proposed controller can be able to achieve better trajectory tracking compared with general computed torque controller.**

I. INTRODUCTION

Parallel robots have advantages such as high stiffness, high precision, high load-carrying capacity over serial manipulators[1]. However, the limited workspace and abundant singularities within the workspace decline its wide application. Based on general parallel manipulator, if passive joints can be replaced with active joints, or other chains with actuation freedom are appended, then redundantly actuated parallel manipulators are obtained[2]. Redundancy parallel robots not only inherit those advantages but also can improve kinematics and dynamics performance[3][4] especially eliminate the actuation singularity[5].

The dynamics equations of parallel mechanisms are the foundation of the controller design; Kane, an American scholar, proposed Kane equation to derive dynamics equations without finding dynamic parameters. This method takes quasi-velocities as independent variables to describe the movement of system; Because there is no need to calculate dynamic function and its derivative, the equations are first-order forms to facilitate computer programming[6]. Due to structure complexity, tightly coupled kinematics and nonlinear dynamic characteristics make controller design for parallel manipulators with redundant actuation difficult.

In traditional field, augmented PD controller and computed torque controller are used. But their effects are not so good because dynamics uncertainty and disturbance exist. To solve this problem, many modern controllers are designed such as adaptive controller[7][8], robust controller[9], sliding mode controller[10]. Actually , those methods are usually combined. However, the structure characteristics and kinematics correlation among chains are not taken into account. To solve this problem, many researchers investigate synchronous control. An controller termed adaptive synchronized controller is used on a P-R-R type parallel manipulator to improve trajectory tracking accuracy[11]. Using cross-coupled error to construct synchronization controller to control a 3-DOF parallel manipulator for its trajectory tracking[12]. A controller termed adaptive synchronized controller is designed to control a robot called CRS A460[13].

Sliding mode variable structure control is used widely due to its advantages: insensitive to system parameters change and outside interference, able to respond fast, unnecessary to identify parameters online. Connecting sliding mode controller which is robust if the control system is in the sliding surface and synchronous control to constitute sliding mode synchronous control. In [14] , a finite time synchronized control with using terminal sliding mode was presented to achieve synchronization error and tracking error converge to zero at the same time for 6-SPS parallel manipulator. To drive the errors to converge to zero simultaneously is very important for robotics control. For multiple motion axes systems, synchronization error is designed in cross-coupling error space to coordinate motion among axes, and a robust adaptive control approach with terminal sliding mode is designed[15]. However, to construct a valid switching surface is not easy. Fuzzy inference mechanism can be helpful for this without accurate model to find better switching surface [16].In general, a fuzzy logic controller is composed of four parts: a fuzzification interface, a knowledge base, an inference engine and a defuzzification interface[17].B. Yoo and W. Ham proposed two fuzzy interference mechanisms to approximate unknown nonlinear system functions and proved the designed controllers were stable and approximated the nonlinear functions well[18].

For a 2-Dof planar parallel manipulator with redundant actuation, many control algorithms have been developed. J. W. Mi proposed synchronization controller to control this structure[19]. W. W. Shang proposed many control methods such as adaptive computed torque[20], adaptive compensation of dynamics and friction8, nonlinear adaptive task space control[21], coordination controller in task space[22].

In this paper, dynamic model is established in the task space based on Kane equation. Based on dynamic model, the controller combining adaptive control, sliding mode control with fuzzy inference mechanism, synchronous control and

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robust control to improve trajectory tracking. Synchronization error is defined by contour error of the desired trajectory. What's following is to determine reference velocity and acceleration to construct sliding mode surface which includes trajectory error and synchronization error. According to dynamic model's properties, the linear parameterization expression with respect to the dynamic parameters is formulated. With this expression, parameters adapting law is obtained with robust parameters compensation. Concluding all above, an adaptive robust fuzzy sliding mode synchronous controller is designed. The convergences of the tracking error and synchronization error as well as their change rate are proved by Lyapunov method and the Barbalat's lemma. With Matlab, the proposed controller is driven to control the 2-Dof planar parallel manipulator with redundant actuation to track a four leaves rose curve. To illustrate validity of the proposed control algorithm, the computed torque controller is implemented.

The paper is organized as follows. In section Ⅱ, the dynamic model is derived in the task space by Kane equation and its several characteristics are listed. In section Ⅲ, a robust adaptive sliding model synchronous controller is designed and convergence of the tracking error and synchronization error as well as their change rate are proved . In section Ⅳ, parameters of switching surface are determined by the fuzzy inference mechanism. In section Ⅴ, Matlab simulation is carried out and the relevant results are compared with the traditional computed torque controller. Finally, conclusions are addressed.

II. DYNAMIC MODEL

A The introduction of the architecture

The architecture of the 2-DOF planar parallel manipulator with redundant actuation is shown in Fig. 1. It consists of three chains with two rotary pairs interacting to compose a platform. As the Fig.1 shows, three servo motors are located at the bases A1, A2, A3 and the end-effector is mounted at joint q where three chains meet. The unit of the frame is a meter. Coordinates of A1, A2 and A3 are (0,0.250), (0.4330,0) and (0.4330,0.5000) separately. Six legs are separately $l_{a1}, l_{b1}, l_{a2}, l_{b2}, l_{a3}, l_{b3}$ and three active joints are q_{a1}, q_{a2}, q_{a3}. All concrete parameters are presented in Table 1.

B Dynamic modelling based on Kane equation

The American scholar Kane put forward Kane equation to derive a dynamic model. Kane equation can be described as: generalized positive forces plus generalized force acted on rigid body equals zero, namely:

$$F + F_k^* = 0 \tag{1}$$

The planar 2-DOF redundantly actuated parallel manipulator can be cut into three 2R serial structures with common constraint. As fig.2 shows, quasi-velocities are $u_1 = \dot{q}_{a1}, u_2 = \dot{q}_{b1}$, we can find dynamics model of this mechanism as

$$\boldsymbol{M}_1 \begin{bmatrix} \dot{u}_a \\ \dot{u}_b \end{bmatrix} + \boldsymbol{C}_1 \begin{bmatrix} u_a \\ u_b \end{bmatrix} = \begin{bmatrix} \tau_a \\ \tau_b \end{bmatrix} \tag{2}$$

Then, the dynamic model of the 2-Dof parallel manipulator in joint space can be derived from(2).

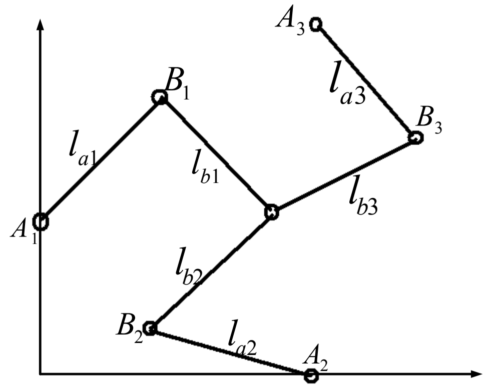


Fig.1 Coordination of the 2-DOF planar parallel manipulator with redundant actuation

Table 1 Parameters of the mechanism

	Link mass	Link length	Mass centre distance	Moment on inertia
l_{a1}	1.2525	0.2440	0.1156	0.0124
l_{b1}	1.0771	0.2440	0.1621	0.0098
l_{a2}	1.3663	0.2440	0.0657	0.0122
l_{b2}	0.4132	0.2440	0.1096	0.0036
l_{a3}	1.3663	0.2440	0.0657	0.0122
l_{b3}	0.4132	0.2440	0.1096	0.0036

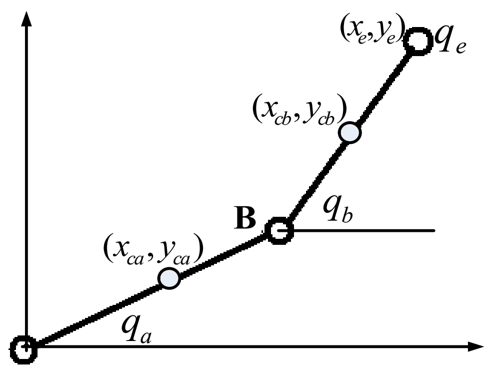


Fig.2 2R serial architecture

Define quasi-velocity of joints and input torque of joints as $\boldsymbol{u} = (u_{a1,} u_{a2,} u_{a3,} u_{b1,} u_{b2,} u_{b3})^T$ $\boldsymbol{\tau} = [\tau_{a1}\ \tau_{a2}\ \tau_{a3}\ \tau_{b1}\ \tau_{b2}\ \tau_{b3}]^T$, then the dynamic model in joint space can be obtained as follows

$$\boldsymbol{M}\dot{\boldsymbol{u}} + \boldsymbol{C}\boldsymbol{u} = \boldsymbol{\tau} \tag{3}$$

Defining quasi-velocity of end-effector as $\boldsymbol{u}_e = (u_{ex} \quad u_{ey})^T$, two Jacobin matrixes from kinematics analysis can be obtained

$$\boldsymbol{J} = \frac{(u_{a1,}u_{a2,}u_{a3,}u_{b1,}u_{b2,}u_{b3})}{(u_{ex}, u_{ey})}, \boldsymbol{S} = \frac{(u_{a1,}u_{a2,}u_{a3})}{(u_{ex}, u_{ey})} \tag{4}$$

Then, it is accessible to elimilate passive variables through the kinematic relationship $\boldsymbol{u} = \boldsymbol{J}\boldsymbol{u}_e$. Substitute it into (3)

$$\boldsymbol{M}\frac{d}{dt}(\boldsymbol{J}\boldsymbol{u}_e) + \boldsymbol{C}\boldsymbol{J}\boldsymbol{u}_e = \boldsymbol{\tau} \tag{5}$$

Finally, dynamics model of the mechanism can be expressed in workspace without passive joint variables as

$$\boldsymbol{M}_e\dot{\boldsymbol{u}}_e + \boldsymbol{C}_e\boldsymbol{u}_e = \boldsymbol{S}^T\boldsymbol{\tau}_a \tag{6}$$

Where, $\boldsymbol{M}_e = \boldsymbol{J}^T\boldsymbol{M}\boldsymbol{J}$, $\boldsymbol{C}_e = \boldsymbol{J}^T(\boldsymbol{M}\dot{\boldsymbol{J}} + \boldsymbol{C}\boldsymbol{J})$. Its Lagrange equation is

$$\boldsymbol{M}_e\ddot{\boldsymbol{q}}_e + \boldsymbol{C}_e\dot{\boldsymbol{q}}_e = \boldsymbol{S}^T\boldsymbol{\tau}_a \tag{7}$$

For dynamic models as (7) shows, several properties are presented as follows[23].

Property 1: inclined symmetry

If $\boldsymbol{N}(\boldsymbol{q},\dot{\boldsymbol{q}}) = \dot{\boldsymbol{M}}_e(\boldsymbol{q}) - 2\boldsymbol{C}_e(\boldsymbol{q},\dot{\boldsymbol{q}})$ $\eta_{j,k} = \eta_{k,j}$ $\eta \in N$ then N is inclined symmetry.

Property 2: dynamic model linearization

$$\boldsymbol{M}_e\ddot{\boldsymbol{q}} + \boldsymbol{C}_e\dot{\boldsymbol{q}} = \boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}},t)\boldsymbol{\Theta} \tag{8}$$

Where, $\boldsymbol{Y}$ is $n \times r$ dimension regression matrix, $\boldsymbol{\Theta}$ is $r \times 1$ dimension vector parameter.

III. ADAPTIVE SLIDING MODE SYNCHRONOUS CONTROLLER DESIGN

A Sliding surface design based on synchronous error

Define trajectory tracking error vector of end-effector as

$$\boldsymbol{e} = \boldsymbol{q}_e^d - \boldsymbol{q}_e \tag{9}$$

Contour error of trajectory can be defined as synchronization error, then the synchronization error is relevant to tracking error

$$\boldsymbol{e}_s = \boldsymbol{H}(t)\boldsymbol{e} \tag{10}$$

Where, $\boldsymbol{H}(t)$ is the relationship matrix between trajectory tracking error and synchronization error. If θ is tangent angle of desired trajectory, then

$$\boldsymbol{H}(t) = \begin{bmatrix} -\sin(\theta)^2 & \frac{1}{2}\sin(2\theta) \\ -\frac{1}{2}\sin(2\theta) & \cos(\theta)^2 \end{bmatrix} \tag{11}$$

Based on (9) and (10), cross-coupling error is

$$\boldsymbol{e}_c = \boldsymbol{e} + \boldsymbol{R}\int_0^t \boldsymbol{e}_s(v)dv \tag{12}$$

Where, $\boldsymbol{R} = diag(r_1, r_2)$ is coupling positive definite matrix. Cross-coupling error contains the trajectory tracking error and the synchronization error. From(12), cross-coupling velocity and acceleration error vectors are

$$\dot{\boldsymbol{e}}_c = \dot{\boldsymbol{e}} + \boldsymbol{R}\boldsymbol{e}_s, \ddot{\boldsymbol{e}}_c = \ddot{\boldsymbol{e}} + \boldsymbol{R}\dot{\boldsymbol{e}}_s \tag{13}$$

Define the sliding surface as:

$$\boldsymbol{s} = \dot{\boldsymbol{e}}_c + \boldsymbol{A}\boldsymbol{e}_c \tag{14}$$

Where, $\boldsymbol{A} = diag(a_1, a_2)$ is positive definite.

B Sliding mode controller design for synchronization

Define reference velocity $\dot{\boldsymbol{q}}_e^r$ and acceleration $\ddot{\boldsymbol{q}}_e^r$ as follows:

$$\dot{\boldsymbol{q}}_e^r = \boldsymbol{s} + \dot{\boldsymbol{q}}_e, \ddot{\boldsymbol{q}}_e^r = \dot{\boldsymbol{s}} + \ddot{\boldsymbol{q}}_e \tag{15}$$

From (15), the following process can be derived

$$\begin{aligned} \boldsymbol{M}_e\dot{\boldsymbol{s}} + \boldsymbol{C}_e\boldsymbol{s} &= \boldsymbol{M}_e(\ddot{\boldsymbol{q}}_e^r - \ddot{\boldsymbol{q}}_e) + \boldsymbol{C}_e(\dot{\boldsymbol{q}}_e^r - \dot{\boldsymbol{q}}_e) \\ &= \boldsymbol{M}_e\ddot{\boldsymbol{q}}_e^r + \boldsymbol{C}_e\dot{\boldsymbol{q}}_e^r - \boldsymbol{\tau}_e \end{aligned} \tag{16}$$

According to property 2 of dynamic models, (16) can be transformed into

$$\boldsymbol{M}_e\dot{\boldsymbol{s}} + \boldsymbol{C}_e\boldsymbol{s} = \boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\dot{\boldsymbol{q}}_e^r,\ddot{\boldsymbol{q}}_e^r)\boldsymbol{\Theta} - \boldsymbol{\tau}_e \tag{17}$$

And control law can be designed as

$$\boldsymbol{\tau}_e = \boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\dot{\boldsymbol{q}}_e^r,\ddot{\boldsymbol{q}}_e^r)\boldsymbol{\Theta} + \varepsilon\,\mathrm{sgn}(\boldsymbol{s}) + \boldsymbol{K}\boldsymbol{s} \tag{18}$$

Where $\boldsymbol{K}=diag(k,k)$ and $\boldsymbol{\varepsilon} = diag(\varepsilon,\varepsilon)$ are symmetric positive definite. $\boldsymbol{Y}(\boldsymbol{q},\dot{\boldsymbol{q}},\dot{\boldsymbol{q}}_e^r,\ddot{\boldsymbol{q}}_e^r)$ is dimensional 2×9 matrix, $\boldsymbol{\Theta} = \int_0^{ts} \boldsymbol{\Gamma}\boldsymbol{Y}^T\boldsymbol{s}dt$,which can be calculated[21]65-66.

C System stability analysis

Before analysis, Barbalat lemma is shown as the following

Barbalat Lemma If a differentiable function $f(t)$ has a limit as $t \to \infty$, and if $\dot{f}(t)$ is uniformly continuous, then $f(t) \to 0$ as $t \to \infty$.

Theorem: the proposed controller (18) guarantees asymptotic convergence to zero both of the trajectory tracking errors and synchronization errors. Namely, the system is globally stable, i.e, when $t \to \infty$, $e \to 0$, $e_s \to 0$.

Proof: Lyapunov function is defined as

$$V = \frac{1}{2}\boldsymbol{s}^T\boldsymbol{M}_e\boldsymbol{s} \tag{19}$$

Differentiating $\boldsymbol{V}$ with respect to time yields

$$\dot{\boldsymbol{V}} = \boldsymbol{s}^T\boldsymbol{M}_e\dot{\boldsymbol{s}} + \frac{1}{2}\boldsymbol{s}^T\dot{\boldsymbol{M}}_e\boldsymbol{s} \tag{20}$$

Considering property 1, then one can have

$$\boldsymbol{s}^T(\frac{1}{2}\dot{\boldsymbol{M}}_e - \boldsymbol{C}_e)\boldsymbol{s} = 0 \tag{21}$$

Combining (19)-(21), one can get

$$\dot{\boldsymbol{V}} = \boldsymbol{s}^T(\boldsymbol{M}_e\dot{\boldsymbol{s}} + \boldsymbol{C}_e\boldsymbol{s}) = \boldsymbol{s}^T(-\varepsilon\,\mathrm{sgn}(\boldsymbol{s}) - \boldsymbol{K}\boldsymbol{s}) \tag{22}$$

It is easy to know $\boldsymbol{K} > 0$, $\boldsymbol{s}^T\boldsymbol{K}\boldsymbol{s} > 0$, $\boldsymbol{s}^T\mathrm{sgn}(\boldsymbol{s}) > 0$, then $\dot{\boldsymbol{V}} < 0$. Hence, the system is globally stable. With the Barbalat Lemma, $s \to 0$ as $t \to \infty$, then one knows $e_c \to 0$ and $\dot{e}_c \to 0$ as $t \to \infty$. Hence, $e \to \infty$ and $e_s \to \infty$ as $t \to \infty$. This control law could realize convergence to zero of the trajectory tracking error and synchronization error at the same time.

Because a sliding model variable structure control has chattering phenomena, which affects the trajectory tracking precision. In order to eliminate chattering, the continuous function $\theta(\boldsymbol{s})$ with relay characteristics is used to replace the function of symbols $\text{sgn}(\boldsymbol{s})$ to restrict the trajectory in a boundary layer of ideal sliding mode.

$$\theta(\boldsymbol{s}) = \frac{\boldsymbol{s}}{|\boldsymbol{s}| + \boldsymbol{\delta}} \tag{23}$$

Where, $\boldsymbol{\delta} = [\delta_1, \delta_2]^T$, δ_1 and δ_2 are small positive numbers.

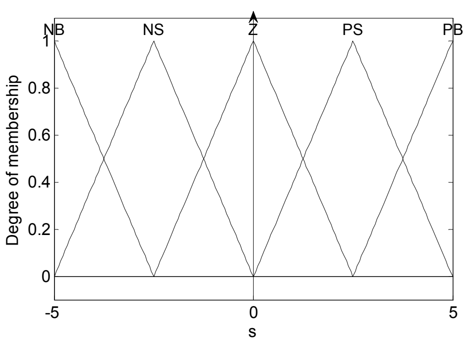
In addition, a robust compensation term $\boldsymbol{r}$ will be added to adaptive term. From (18) and (23), the adaptive robust sliding mode synchronous control law can be expressed as

$$\boldsymbol{\tau}_e = \boldsymbol{Y}(\boldsymbol{q}, \dot{\boldsymbol{q}}, \dot{\boldsymbol{q}}_e^r, \ddot{\boldsymbol{q}}_e^r)(\boldsymbol{\Theta} + \boldsymbol{r}) + \boldsymbol{\varepsilon}\theta(\boldsymbol{s}) + \boldsymbol{K}\boldsymbol{s} \tag{24}$$

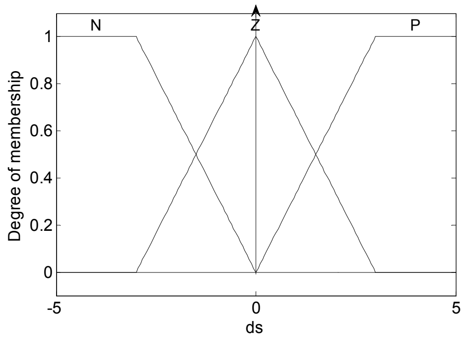
Where, $\boldsymbol{r} = \dfrac{r\boldsymbol{Y}^T\boldsymbol{s}}{\|\boldsymbol{Y}^T\boldsymbol{s}\|}$, r is a positive number.

IV. ADAPTIVE FUZZY SLIDING MODE SYNCHRONOUS CONTROLLER DESIGN

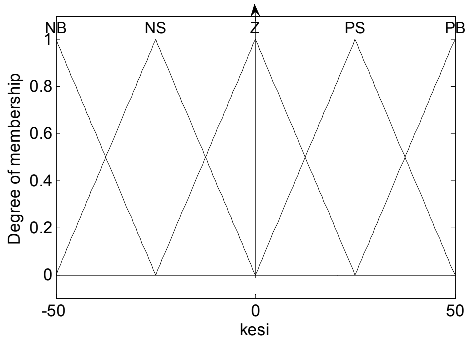
In control law (24), values of $\boldsymbol{\varepsilon}$ and $\boldsymbol{K}$ influence the performances of controller. To obtain the best matching values, a fuzzy inference mechanism is proposed to build up a fuzzy sliding mode controller. In this fuzzy inference system, variables are S and $\dot{S}$ (inputs) and $\boldsymbol{\varepsilon}$ and $\boldsymbol{K}$ (outputs). For this sliding mode surface, some linguistic values are defined as: NB(Negative Big), NM(Negative Medium), NS(Negative Small), N(Negative), Z(Zero), P(Positive), PS(Positive Small), PM(Positive Medium), PB(Positive Big). The membership functions for two inputs and two outputs are depicted in Fig. 3. The fuzzy inference mechanism contains 15 rules. And those rules are summarized in the Table 2 and Table 3. Those rules are deduced from the knowledge of sliding mode control. If S is negative big and its derivative is negative, then the control input $\boldsymbol{\varepsilon}$ and $\boldsymbol{K}$ need to be negative big to move the representative point of the system closer the sliding line.



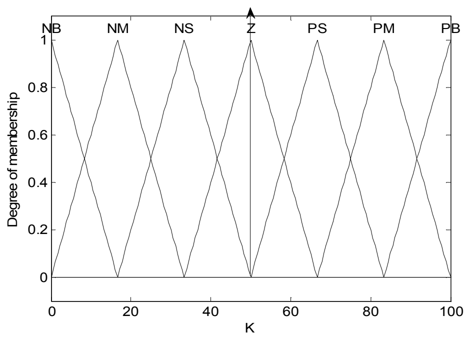
(a) Memberships for S



(b) Memberships for $\dot{S}$



(c) Memberships for $\boldsymbol{\varepsilon}$



(d) Memberships for $\boldsymbol{K}$

Fig. 3 Memberships for parameters of switching surface

Table 2 Rules for $\boldsymbol{\varepsilon}$

	NB	NS	Z	PS	PB
N	NB	NS	Z	PS	PB
Z	NS	Z	PS	PB	PB
P	NS	Z	PS	PB	PB

Table 3 Rules for $\boldsymbol{K}$

	NB	NS	Z	PS	PB
N	NB	NM	NS	Z	PS
Z	NB	NM	NS	Z	PM
P	NM	NS	Z	PS	PB

V. MATLAB SIMULATION

Now, the end-effector of the 2-Dof redundantly actuated parallel robots is driven to track a four leaves rose curve whose function is shown in follows.

$$\begin{cases} r = 0.1\sin(2t) \\ x(t) = 0.3 + r\cos(t) \\ y(t) = 0.25 + r\sin(t) \end{cases} \tag{25}$$

And the curve's trajectory is shown in Fig.4. It starts as t equals zeros and ends as t equals 2π. To demonstrate that the proposed controller can improve trajectory tracking accuracy, simulation of using computed torque controller is implemented. In computed torque controller, the control law is[20]460

$$\boldsymbol{\tau}_e = \boldsymbol{M}_e(\ddot{\boldsymbol{q}}_d + \boldsymbol{K}_p\boldsymbol{e} + \boldsymbol{K}_d\dot{\boldsymbol{e}}) + \boldsymbol{C}_e\dot{\boldsymbol{q}} \tag{26}$$

Define $\boldsymbol{K}_p = diag(900,900)$, $\boldsymbol{K}_d = diag(150,150)$. And in control law (24), $\boldsymbol{R} = diag(10,10)$, $\boldsymbol{A} = diag(50,50)$, $\boldsymbol{\delta} = diag(0.5,0.5)$, $r = 5$. $\boldsymbol{\varepsilon}$ and $\boldsymbol{K}$ can be determined by fuzzy inference mechanism. To verify the validity of the proposed controller, tracking errors and synchronization errors changing with time of two controllers are presented in Fig.5. As Fig.5 shows, tracking errors and synchronization errors of the proposed controller change gradually around the zero line. From Fig. 5, we know that proposed controller can achieve better trajectory tracking compared with computed torque.

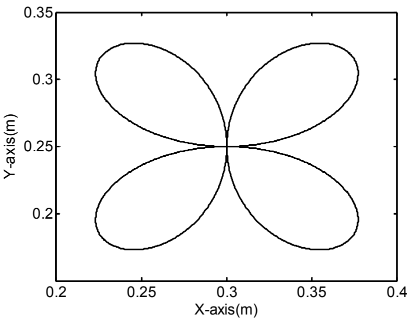
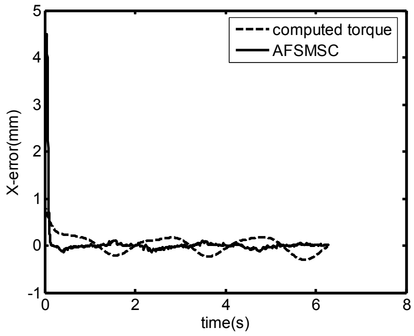
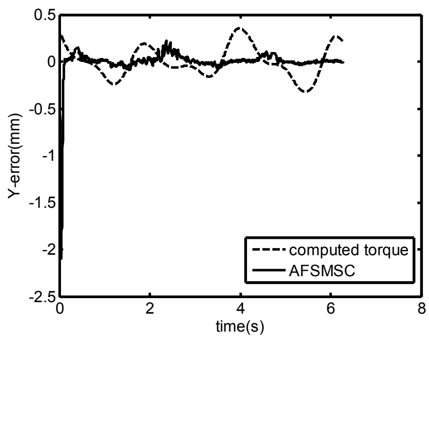


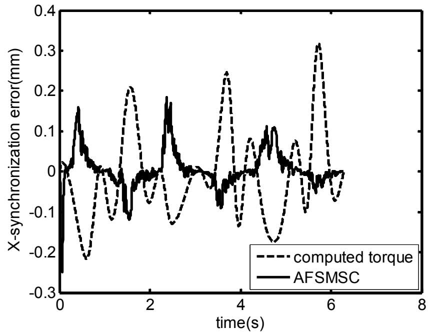
Fig.4 Desired trajectory



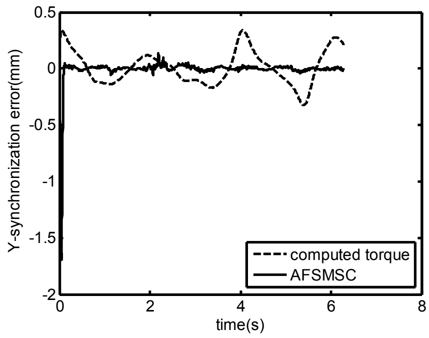
(a) X-errors



(b) Y-errors



(c) X-synchronization errors



(d) X-synchronization errors

Fig.5 Errors comparison of two algorithms

VI. CONCLUSIONS

The dynamic model of the planar 2-DOF parallel manipulator is derived easily using Kane equation. Based on the dynamic model, the adaptive robust fuzzy sliding mode synchronous controller is designed to control the mechanism to track a four leaves rose curve. By Lyapunov stability proof, it can be concluded that both trajectory tracking errors and synchronization errors can converge to zero simultaneously by using the proposed controller. Matlab simulation gives errors comparison of the proposed control algorithm and computed torque method. From those figures, the tracking errors decrease greatly with the proposed controller compared with computed torque controller. And fuzzy inference mechanism can help find optimal parameters of sliding mode control.

However, there is still a problem that needs to be tackled in the future: there is no a systematic approach in establishing the fuzzy control system and it is dependent on the knowledge of an expert heavily.

REFERENCES

[1] J. P. Merlet. Parallel Robots, Norwell, MA: Kluwer(2000).
[2] S. Kock and W. Schumacher, "A Parallel x-y Manipulator with Actuation Redundancy for High-speed and Active-stiffness Application," Proceedings of IEEE International Conference on Robotics and Automation, Leuven, Belgium(1998), p. 2295-2300.

[3] W. W. Shang and S. Cong, “Study on Force Transmission Performance for Planar Parallel Manipulator,” Proceedings of the 6th World Congress on Intelligent Control and Automation, Dalian, China(2006), p. 8098-8102.

[4]J. Wu, J. S. Wang, T. M. Li, et al., “Performance Analysis and Application of a Redundantly Actuated Parallel Manipulator for Milling,” Journal of Intelligent and Robotic Systems, Vol. 50, No. 2(2007), p. 163-180.

[5] I. Ebrahimi, J. Carretero, and R. Boudreau, “3-PRRR Redundant Planar Parallel Manipulator: Inverse Displacement, Workspace and Singularity Analyses,”, Mechanism and Machine Theory, vol. 42, No. 8(2007), p. 1007-1016.

[6] T. R. Kane, D. A. Levinson , Dynamics, Theory and Applications[M]. New York: McGraw-Hill Book Company(1985).

[7] R. Ortega, M. W. Spong, “Adaptive motion Control of Rigid Robots: a Tutorial,” Proceedings of the 27th Conference on Decision and Control, Austin, Texas(1988), p.1575-1584.

[8] W. W. Shang, S. Cong, “Adaptive Compensation of Dynamics and Friction for a Planar Parallel Manipulator with Redundant Actuation,” Proceedings of the 2010 IEEE International Conference on Robotics and Biomimetics, Tianjin(2010), p.507-512.

[9] D. B. Xu, J Huang, “Robust Adaptive control of a class of Nonlinear Systems and its Applications,” IEEE Transactions on Circuits and Systems: Regular Papers, Vol. 57, No. 3,(2010), p.691-702.

[10] G. Yang, X. Y. Fu and B. R. Li, “Research on 2-DOF Parallel Manipulator with Redundant Actuation,” Journal of System Simulation, Vol.18, No.2(2006), p. 416-139+423.

[11] L. Ren, J. K. Mills, “Adaptive Synchronized Control for a Planar Parallel Manipulator: Theory and Experiments, ” Transactions of ASME, Vol. 128(2006), p. 976-979.

[12] D. Sun, R. Lu, J. K. Mills et al, “Synchronous Tracking Control of Parallel Manipulators Using Cross-coupling Approach,” The International Journal of Robotics Research, Vol. 25, No. 11(2006), p. 1137-1147.

[13] D. Sun and K.M. James, “Adaptive Synchronized Control for Coordination of Multirobot Assembly Tasks,” IEEE Transactions on Robotics and Automation, Vol. 18, No. 4, 2002, pp. 498-510.

[14] D Y Zhao, S Y Li, F Gao. Finite time position synchronised control for parallel manipulators using fast terminal sliding mode. Internatinal Journal of Systems Science, Vol. 40, No. 8, 2009, p. 829-843.

[15] D. Zhao, S. Li, F. Gao, et al. Robust adaptive terminal sliding mode-based synchronised position control for multiple motion axes systems, IET Control Theory Applications, Vol.3 No. 1, 2009, p. 136-150.

[16] F-J. Lin and S. L. Chiu. “Adaptive fuzzy sliding-mode control for PM synchronous servo motor drives,” IEEE Proceedings of Control Theory Application, Vol1. 105, No. 1, 1998.

[17] M. J. Er, S. M. Yap, C.W. Yeaw, et al. A review of neural-fuzzy controllers for robotic manipulators. Proceedings of IEEE International Conference on Industry Applications, Vol.2, 1997, p. 812-819.

[18] B. Yoo and W. Ham. Adaptive Fuzzy Sliding Mode Control of Nonlinear System. IEEE Transactions on Fuzzy Systems, Vol. 6, No. 2, 1998, p. 315-342.

[19] J. W. Mi, H. D. Wang, B. Hong et al, “Synchronization Control of Planar 2-DOF Robot with Redundant Actuation,” International Journal of Plant Engineering and Management, Vol. 16, No. 1(2011), p. 35-40.

[20] W. W. Shang, S. Cong and Y. Ge, “Adaptive Computed Torque Control for a Parallel Manipulator with Redundant Actuation,” Robotica, Vol. 30(2012), p. 457-466.

[21] W. W. Shang and S. Cong, “Nonlinear Adaptive Task Space Control for a 2-DOF Redundantly Actuated Parallel Manipulator,” Nonlinear Dynamics, Vol. 59(2010), p. 61-72.

[22] W. W. Shang and S. Cong, “Coordination Control of Parallel Manipulators with Actuation Redundancy,” 48th IEEE Conference on Decision and Control and 28th Chinese Control Conference(2009), p. 8186-8191.

[23] W. S. Mark, H. M. Seth and Vidyasagar. Robot Modeling and Control[M]. JOHN WILEY & SONS, INC(2005).