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A Practical Method for Controlling the Parallel Robot Path Based on the Sliding Mode Method with Fuzzy Adjustable Coefficients

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ABSTRACT: Parallel manipulators are of interest in various industries due to their high precision, rigidity, high speed and low inertia. Controlling these types of systems faces challenges due to their complex and non-linear dynamics. Among the many methods of controlling the path of parallel manipulators, computed torque and sliding mode methods are the famous methods that are proposed. In practical applications, when the speed of the robot increases, adjusting the controller parameters is very difficult and depends on the working conditions of the robot, so the robot cannot work properly with fixed and predetermined coefficients under any condition. The type of path, the speed of the robot along the path, the initial conditions of the end effector of the robot in relation to the path, and even the sampling time are factors that affect the accuracy of the controller, and by changing each of them, it may be necessary to redefine the parameters of the control system and change the control coefficients. In this article, a method is presented which is based on the sliding mode method and the coefficients of the control system are adjusted appropriately by changing the sliding surface and sliding speed using the fuzzy method. The performance of this method has been investigated in two ways: modeling in MATLAB software and real time applying it to a planar parallel robot.

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1- Introduction

Parallel manipulators consist of several independent kinematic chains. All the mentioned chains are connected to the fixed base on one side and to the mobile base on the other side. Compared to serial manipulators, parallel dexterous arms have potential advantages in accuracy, robustness, and the ability to carry heavy loads [1]. Parallel manipulators are subject to uncertainties that may be caused by the unknown nonlinear dynamic model, nonlinear friction forces, unknown uncertainties, and external disturbances. These uncertainties weaken the performance of the control system. Therefore, precise trajectory control for parallel dexterous arms is a challenging task, especially at high speeds with various uncertainties [2].

Due to good robustness of sliding mode control against uncertainties, ability to overcome external disturbances and ease of implementation. This method has attracted a lot of attention among the control methods of nonlinear systems, especially for the control of parallel or serial manipulators [3]. However, this method has shortcomings, most of which are due to the use of fixed control gains in the switching part as well as the slope of the sliding surface [4]. In this control method, increasing the gain of the controller increases the robustness of the system, but increasing the gain is limited because it aggravates the undesirable phenomenon of chattering as well as the saturation of actuators. On the other hand, reducing the controller gains reduces the performance and robustness of the controller and increases the tracking error. For this reason, the proper adjustment of sliding mode controller coefficients has been widely considered by the control community in recent years [5].

In this article, in order to trajectory control of a five-bar parallel plannar robot, a method based on the sliding mode is presented, whose gains are adjusted automatically and online by the fuzzy method. The results of the work have been evaluated by simulation in MATLAB software and also by practical implementation on a robot.

2- Modeling

Since the control methods considered in this article work based on the system model, first it is necessary to introduce the robot model and briefly mention its dynamic equations.

2- 1- Manipulator sepecifications

The image of the parallel robot analyzed in this article can be seen in Figure 1. The length of the arms, the absolute rotation of the joints and the distance of each joint to the center of mass of the arm are represented by l_i, θi, and l_{gi} respectively. The mass of the arms is expressed by m_i and the mass moment of inertia relative to the center of mass

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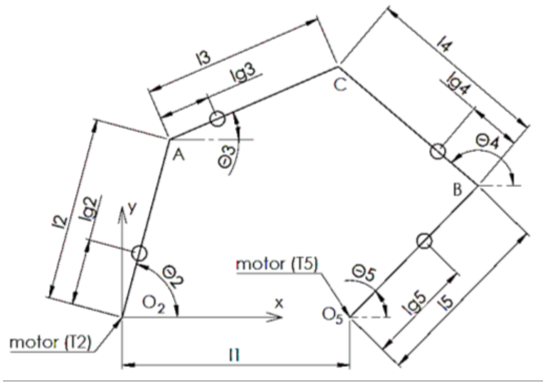

Fig. 1. Coordinate system and parametrs used in equations.

of the arm are expressed by J_i. The robot has two motors whose torques are expressed as T_2 and T_5 respectively. The specifications of the robot are given in Table 1.

2- 2- Dynamic equations

The dynamic equations of the robot are obtained using Lagrange's equations in the form of the equation (1).

The angular position and angular velocity of the robot arms are defined as state variables in the form of equation (2). f_i, h_i and g_i $(i=2, 3, 4, 5)$ are non-linear functions of the state vector obtained from the robot dynamics.

$$\dot{\vec{x}}=\begin{Bmatrix}\dot{x}_1\\\dot{x}_2\\\dot{x}_3\\\dot{x}_4\\\dot{x}_5\\\dot{x}_6\\\dot{x}_7\\\dot{x}_8\end{Bmatrix}=\begin{Bmatrix}x_5\\x_6\\x_7\\x_8\\f_2(\vec{x})\\f_3(\vec{x})\\f_4(\vec{x})\\f_5(\vec{x})\end{Bmatrix}+\begin{bmatrix}0&0\\0&0\\0&0\\0&0\\h_2(\vec{x})&g_2(\vec{x})\\h_3(\vec{x})&g_3(\vec{x})\\h_4(\vec{x})&g_4(\vec{x})\\h_5(\vec{x})&g_5(\vec{x})\end{bmatrix}\begin{Bmatrix}T_2\\T_5\end{Bmatrix}\tag{1}$$

$$\begin{gathered}\vec{x}=[x_1\quad x_2\quad x_3\quad x_4\quad x_5\quad x_6\quad x_7\quad x_8]^T=\\ [\theta_2\quad \theta_3\quad \theta_4\quad \theta_5\quad \dot{\theta}_2\quad \dot{\theta}_3\quad \dot{\theta}_4\quad \dot{\theta}_5]^T\end{gathered}\tag{2}$$

3- Control

Using the **coputed torque control method**, the control law for trajectory control of this robot can be expressed by equation (3).

$$\begin{Bmatrix}T_2\\T_5\end{Bmatrix}=\begin{bmatrix}h_2(\vec{x})&g_2(\vec{x})\\h_5(\vec{x})&g_5(\vec{x})\end{bmatrix}^T\left(-\begin{Bmatrix}f_2(\vec{x})\\f_5(\vec{x})\end{Bmatrix}+\begin{Bmatrix}n_2\\n_5\end{Bmatrix}\right)\tag{3}$$

Where n_i is expressed as equation (4).

Table 1. Specifications of the robot

l_1	310 mm	m_3	0.495 kg
l_2	250 mm	m_4	0.449 kg
l_3	250 mm	J_{o2}	11.7×10^{-3} kg.m^2
l_4	250 mm	J_3	4.49×10^{-3} kg.m^2
l_5	250 mm	J_4	5.51×10^{-3} kg.m^2
l_{g3}	134 mm	J_{o5}	12.0×10^{-3} kg.m^2
l_{g4}	126 mm		
Actuators	400 W AC Servo Motor (ECMA-C20604RS)		
Driver	Delta Standard AC Servo Drive (ASDA-B2 Series)		

$$\begin{cases}n_2=\ddot{\theta}_{2d}-2\lambda_2\dot{\tilde{\theta}}_2-\lambda_2^2\tilde{\theta}_2\\ n_5=\ddot{\theta}_{5d}-2\lambda_5\dot{\tilde{\theta}}_5-\lambda_5^2\tilde{\theta}_5\end{cases}\tag{4}$$

Using the **sliding model control method**, the torque of the motors can be calculated as equation (5).

$$\begin{Bmatrix}T_2\\T_5\end{Bmatrix}=\begin{Bmatrix}\hat{T}_2\\\hat{T}_5\end{Bmatrix}-\begin{bmatrix}k_2&0\\0&k_5\end{bmatrix}\begin{Bmatrix}\tanh\left(\dfrac{s_1}{\Phi_1}\right)\\\tanh\left(\dfrac{s_2}{\Phi_2}\right)\end{Bmatrix}\tag{5}$$

Where in

$$\begin{gathered}\begin{Bmatrix}\hat{T}_2\\\hat{T}_5\end{Bmatrix}=\begin{bmatrix}h_2(\vec{x})&g_2(\vec{x})\\h_5(\vec{x})&g_5(\vec{x})\end{bmatrix}^{-1}\\ \left(\begin{Bmatrix}\ddot{\theta}_{d_2}\\\ddot{\theta}_{d_5}\end{Bmatrix}-\begin{bmatrix}\lambda_2&0\\0&\lambda_5\end{bmatrix}\begin{Bmatrix}\dot{\theta}_2-\dot{\theta}_{d_2}\\\dot{\theta}_5-\dot{\theta}_{d_5}\end{Bmatrix}-\begin{Bmatrix}f_2(\vec{x})\\f_5(\vec{x})\end{Bmatrix}\right)\end{gathered}\tag{6}$$

In equation (5), k_i represents the weight of the two parts of the controller, and the value of Φ_i is used to eliminate chattering and allows the system to be located around the plane s=0 as much as the boundary condition Φ_i, if necessary. λ_i, k_i, *and* Φ_i are constants that are determined based on the expected performance of the system.

One of the shortcomings of this method is that the control constants for one input and initial conditions may not be suitable for other conditions and initial inputs, and it is necessary to re-tune these constants for different conditions.

According to equation (5), it can be seen that in the sliding mode method, the control signal consists of two parts. The first part ($\hat{T}_i$) depends on the dynamics of the system and the second part depends on the sliding surface. In this paper, the second part of the control signal (T_f) is tried to be obtained

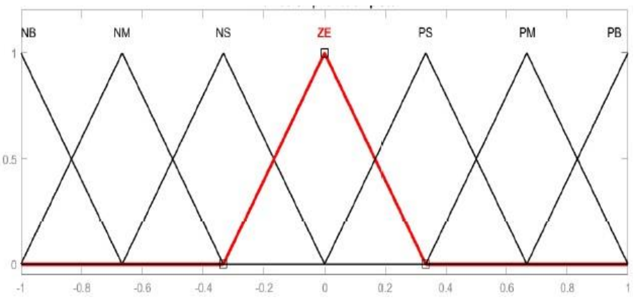

Fig. 2. Membership function diagram of fuzzy variables and fuzzy outputs.

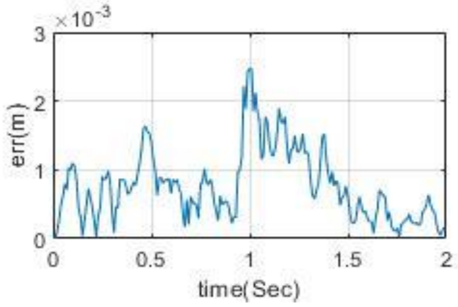

Fig. 4. The initial position and speed of the robot's hand are in accordance with the desired values.

Table 2. Fuzzy rules for calculating T_f

	T_f	s						
		NB	NM	NS	ZE	PS	PM	PB
$\dot{s}$	NB	**PB**	**PB**	**PB**	**ZE**	**ZE**	**ZE**	**ZE**
	NM	**PB**	**PB**	**PB**	**ZE**	**ZE**	**ZE**	**NS**
	NS	**PB**	**PB**	**PM**	**ZE**	**ZE**	**NS**	**NM**
	ZE	**PB**	**PM**	**PS**	**ZE**	**NS**	**NM**	**NB**
	PS	**PM**	**PS**	**ZE**	**ZE**	**NM**	**NB**	**NB**
	PM	**PS**	**ZE**	**ZE**	**ZE**	**NB**	**NB**	**NB**
	PB	**ZE**	**ZE**	**ZE**	**ZE**	**NB**	**NB**	**NB**

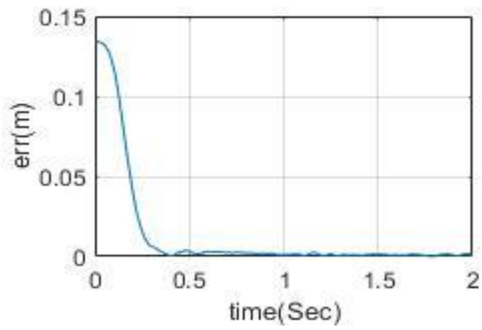

Fig. 5. The robot's hand is 13 cm away from the path, but the speed of the hand and the desired speed are the same and zero.

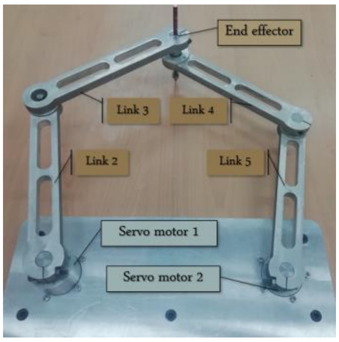

Fig. 3. The five-bar parallel robot on which the results of the article have been analyzed.

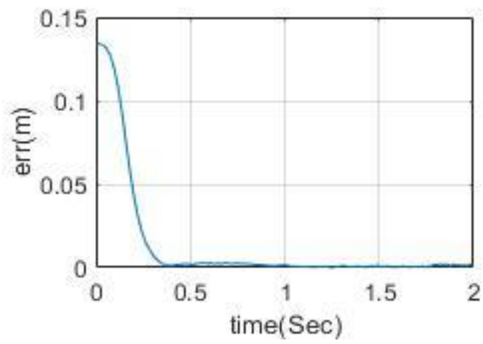

Fig. 6. The initial position and speed of the path are different from the initial conditions of the robot.

automatically by the fuzzy method. This part of the signal depends on the distance of the system states from the sliding surface.

In this method, all three variables $s, \dot{s}, T_f$ are normalized in the range [-1,1] and as large negative (NB), medium negative (NM), small negative (NS), zero (ZE), small positive (PS), medium positive (PM) and large positive (PB) are categorized. The graph of the membership function of all three variables will be the same as in Figure 2.

Fuzzy rules are also written in the form of Table 2.[6]

4- Discussion and Results

In this research, in order to trajectory control of the robot shown in Figure 3, three control methods "Calculated torque", "Sliding mode" and "Fuzzy sliding mode" have been applied and the results have been compared. As can be seen in figures 4 to 6, the performance of the fuzzy sliding model method is very suitable and the control parameters are automatically adjusted with the given fuzzy rules so that the response of the system is a desirable response. Therefore, manual adjustment of control gains is not necessary.

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