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Unactuated Force Control of 5-DOF Parallel Robot Based on Fuzzy PI

Shu-Huan Wen*, Wei Zheng, Shi-Dong Jia, Zhi-Xin Ji, Peng-Cheng Hao, and H.K. Lam

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Abstract: This paper investigates the fuzzy position/force hybrid control for a class of 5-degree-of-freedom (DOF) redundantly actuated parallel robots. The position control law is designed based on the proportional-integral-differential (PID) for the 5-DOF redundantly actuated parallel robot. The fuzzy proportional-integral (PI) redundant actuation force control law is designed based on the position/force hybrid control structure for the 5-DOF redundantly actuated parallel robot. The optimum driving force is obtained in the presence of interference, and the force tracking performance of the fuzzy PI controller is better than the conventional PI controller under the interference condition. Based on the fuzzy position/force hybrid controller, the tracking performance of the closed-loop system for the 5-DOF redundantly actuated parallel robot is improved by using the fuzzy position/force hybrid controller and the interference is eliminated effectively in the control system design. Finally, the co-simulation results of ADAMS and MATLAB/SIMULINK are given to show the effectiveness and advantages of the proposed methods compared with the conventional PI controller.

Keywords: Position/force hybrid control, parallel robots, redundant actuation, fuzzy control.

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1. INTRODUCTION

Parallel Manipulator (PM) [1] is a mechanical system combining parallel mechanism principle with modern robot techniques, which has better real-time, more precision and higher stiffness than the traditional PM. However, due to the feature of the parallel manipulator and environmental uncertainty, the parallel robot has the characteristics including singularity, smaller workspace and strong coupling. These characteristics can make the machine damage resulting from large internal force. Redundant actuation introduced into parallel manipulator is an effective solution. The redundancy of the mechanism includes kinematics and actuation redundancy, which can avoid the singularity effectively. In [2], a kinematic redundant structure was presented for a 3-DOF spherical parallel mechanism (3-RRR PM). A movable prismatic joint is used at the bottom of each branch for the parallel mechanism to enlarge the dexterous working space of 3-RRR PM. A fast 6-DOF PM with redundant actuation was developed [3] and a new parallel mechanism with 6-DOF redundantly actuated pair-universal prismatic pair-sphere pair (UPS) was presented [4]. The redundant structure and a similar non-redundant structure are compared in this paper.

The 6-prismatic pair-universal pair-sphere pair (PUS) parallel mechanism is added to a low degree of freedom universal joint prismatic pair-universal joint (UPU) constraint in the middle branch. The degree of freedom for the UPU branch is five and the platform is 5-DOF based on the screw theory [5]. Thus, the mechanism is a kind of redundant actuation structure. The redundant actuation was used to optimize the system performance characterized by the performance indexes in terms of driving force, energy consumption and internal force [6-8]. The redundant actuation was used to improve the dynamic performance by using scaling factors including the stiffness and forces of the driving joints [9-11]. In [5, 12], the kinematics and workspace were studied for a 5-DOF parallel robot with redundancy and the inverse kinematic solutions were obtained. The redundant actuation parallel robot was implemented in a simulation experiment platform by using the Pro/E software for verification and the obtained results show an improvement in driving force. Although many literatures have worked on the structure design and performance analysis, few investigations have studied the position/force hybrid control for the dynamic model of the redundant drive parallel robot.

Fuzzy logic control theory has been used widely in

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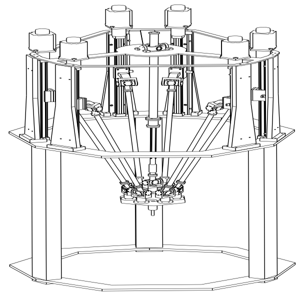
many fields and engineering systems. The unmodeled dynamics exist in many practical systems, thus the adaptive neural controller was designed for a class of nonlinear systems with unmodeled dynamics and immeasurable states [13]. It is well known that the fuzzy logic control theory is a powerful tool to deal with nonlinear systems due to the universal approximation properties [14]. Motivated by this fact, an improved state-feedback adaptive fuzzy design method was proposed for a class of nonlinear systems such that the computation burden was reduced [15]. This is achieved by constructing the biggest adaptive parameter when the system model is n-dimension [15]. With the above discussions, the fuzzy output tracking control was investigated for a class of switched nonlinear systems with non-affine form and non-lower triangular structure. By using the adaptive fuzzy tracking control, the performance of the closed-loop system is improved [16]. Moreover, a new fuzzy PI controller was proposed for the application of the Stewart platform, and this kind of controller did better in the trajectory tracking than the conventional PI controller [17]. Besides, combing the sliding mode control and fuzzy reasoning, the neural network controller was proposed and tested in the 2-DOF robotic manipulator system [18]. A kind of fuzzy proportional-integral-derivative (PID) controller was designed for the three-cylinder hydraulic parallel robot [19]. The proposed algorithm with the fuzzy controller was used to improve the system performance, and it has better control performance than the conventional PID controller.

With the above discussions, it can be seen that the unbalanced branch force will produce a large internal force in the 6PUS-UPU parallel robot, which will lead to a serious impact on the accuracy of the movement for the machine. Thus, the balance of each circuit can be realized and the internal force can be reduced by optimizing the driving force, so that the motion accuracy of the machine frame can be improved. Meanwhile, some optimization methods were proposed in some references [20-25]. For example, the optimization control method base on the artificial neural network (ANN) was proposed, so that the predicted peak point becomes more accurate [20]. The network accuracy is improved by optimizing the number of neurons in the hidden layer. The model estimation accuracy is improved by the improvement of different methods [21-23]. In this paper, the force of two-norm minimization method is used to achieve the optimization of the 6PUS-UPU machine driving force. Although the Smith predictive compensator was designed based on the T-S fuzzy model to solve the time delay problem of in 6PUS-UPU parallel robot, the smart control scheme was not studied [24]. Besides, the model predictive control (MPC) algorithm was introduced into the torque control for redundancy to improve the tracking accuracy of the parallel robot [25]. However, most of the existing methods require to establish an accurate model of the motor vector, which is more complex. Thus, this paper investigates the fuzzy position/force hybrid control for a class of 5-degree-of-freedom (DOF) redundantly actuated parallel robots. The contributions of this paper are listed as: (i) The redundant force branch of the parallel robot is improved and a new redundant actuated force control structure is proposed in this paper. (ii) Based on the novel control structure, a fuzzy PI controller is designed in the redundant actuation branch to obtain optimal solutions under interference condition. (iii) From the simulation results and analysis, it can be seen that the driving forces and poses errors are reduced by designing the fuzzy PI control structure rather than the conventional PI controller.

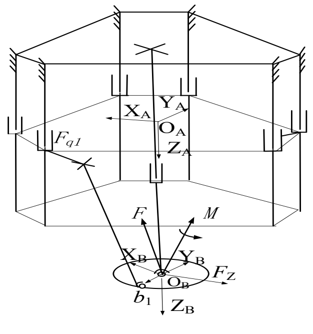
This paper is organized as follows. In section 2, the dynamic equation of the 6PUS-UPU robot model is given. In section 3, the controller is designed for the 6PUS-UPU robot model. In section 4, the simulation results and analysis are presented for the closed-loop system. Finally, the conclusions are given in section 5.

2. DYNAMICS MODELING

In this section, the dynamic equation of the 6PUS-UPU robot model is given [26, 27]. KANE equation is obtained by analyzing the velocity and acceleration of the 6PUS-UPU robot, where the using details of the parameters are given in [26]. The driving force is optimal when the driving force is smaller, then the dynamics analysis of the 6PUS-UPU robot model will provides a model for the simulations [26]. The architecture of the 6PUS-UPU redundant actuation parallel robot is shown in Fig. 1 [26]. In Fig. 1 (a), two platforms are connected by six actuators connecting and a constraint branch. One platform is a mobile platform and the other is a fixed platform. The mobile platform and the fixed platform is connected by the universal joint of the constraint branch. In Fig. 1 (b), O_A is the origin of the fixed platform coordinate system and O_B is the origin of the mobile platform coordinate system.



(a) model of the 6PUS-UPU robot



(b) coordinate system of the 6PUS-UPU robot

Fig. 1. Architecture of the 6PUS-UPU redundant actuation parallel robot [26].

The general form of the dynamic equation is described according to KANE equation [26]

$$G\tau = F'^{T} \tag{1}$$

where G is the Jacobian matrix between the driving forces and platform, F'^{T} is the rest part of the KANE equation [28]. τ is the driving force vector and defined as

$$\tau = \begin{bmatrix} F_{q1} & F_{q2} & F_{q3} & F_{q4} & F_{q5} & F_{q6} & M_c \end{bmatrix}$$

where F_{q1}, F_{q2}, F_{q3}, F_{q4}, F_{q5} and F_{q6} are the driving forces of the six branches.

The optimization problem of driving force can be described as [26]

$$\begin{cases} min\ Z = \tau^{T} W \tau \\ s.t.\ \ G\tau = F'^{T} \end{cases} \tag{2}$$

where W is a diagonal weighted matrix [26]. For the problem formulated, the parameter Z' is introduced as follows

$$Z' = \tau^{T} W \tau + \lambda^{T}\left(F'^{T} - G\tau\right)$$

where λ is the Lagrange factor.

The 6PUS-UPU parallel robot has six branches but only five degrees of freedom, so it can be solved and expressed by the myriad combinations of the driving force. That is, the driving force must be optimized. The equation (3) is the result of seeking extreme value for Z', and it is the smallest combination of the driving force for Z'. So it must satisfy the following constraints.

$$\begin{cases} \dfrac{\partial Z'}{\partial \tau} = 2\tau^{T} W \text{-} \lambda^{T} G = 0 \\ \dfrac{\partial Z'}{\partial \lambda} = F'^{T} \text{-} G\tau = 0 \end{cases} \tag{3}$$

Then we can get.

$$\tau = \frac{1}{2}\left(W^{-1}\right)^{T} G^{T} \lambda \tag{4}$$

Then we can obtain equation (5) from equation (3) to equation (4) [26]

$$\tau = \left(W^{-1}\right) G^{T}\left(G\left(W^{-1}\right) G^{T}\right)^{-1} F'^{T} \tag{5}$$

Then

$$\tau = G^{T}\left(GG^{T}\right)^{-1} F'^{T} = G^{+} F'^{T} \tag{6}$$

where G is a non-invertible matrix [28] and G^{+} is the pseudo-inverse matrix [26]. These equations from equation (1) to equation (6) give the solution of the driving force where equation (6) gives the detailed expression of the driving force.

Remark 1. The 6PUS-UPU parallel robot is a kind of multi-input multi-output, coupled and highly nonlinear system. Compared with other similar methods, the conventional control methods are no longer effective for this complex 6PUS-UPU parallel robot. In this paper, the new redundant actuated force control structure is proposed in this paper based on the position/force hybrid closed-loop control structure.

3. CONTROLLER DESIGN

Task-space control [29, 30] and joint-space control [31, 32] are two common schemes. The joint-space control is good when considering the computational burden and experimental applications [33]. However, this structure will influence the performance of the parallel robot because the redundant force branch is not appropriate for 6PUS-UPU robot in real situation. The robot will be damaged easily when it is in the case of load and fast speed. For redundant parallel robots, the force and overall stiffness of the robot should be improved to ensure the maximum instantaneous driving force and the instantaneous driving force of each driver reach the minimum.

3.1. Position controller design

Position/force hybrid control has higher force control accuracy and tracking capability. By observing and analyzing the 6PUS-UPU robot structure, the uncertainty of the dynamics model and friction influence can be compensated by using the redundant branch to provide the additional compensation dosage [26]. In the next section, we propose two control schemes to control the active stiffness of the mechanism by controlling the input force in the redundant branches. And the force optimization can improve the motion precision of the parallel robot.

The position vector P of the 6PUS-UPU is defined as follows

$$P = \begin{bmatrix} x & y & \varphi \end{bmatrix}^{T} \tag{7}$$

where x, y and φ are the coordinates of the 6PUS-UPU in the coordinate frame,

From (7), one has

$$\dot{\theta} = J^{+}\dot{P} \tag{8}$$

where J^{+} is pseudo inverse matrix of J and defined as follows

$$J^{+} = \left(J^{T}J\right)^{-1} J^{T} \tag{9}$$

with

$$J = \begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \\ j_{31} & j_{32} \end{bmatrix} \tag{10}$$

in which

$$\begin{aligned} j_{11} &= (r/2)cos\,\varphi - (r/l)(d\,sin\,\varphi) \\ j_{12} &= (r/2)cos\,\varphi + (r/l)(d\,sin\,\varphi) \\ j_{21} &= (r/2)sin\,\varphi + (r/l)(d\,cos\,\varphi) \\ j_{22} &= (r/2)sin\,\varphi - (r/l)(d\,cos\,\varphi) \\ j_{31} &= r/l, \qquad j_{32} = -r/l \end{aligned} \tag{11}$$

where l is the link length of 6PUS-UPU, r is the distance between the centroid and link.

Taking the time derivative of $\dot{\theta}$

$$\ddot{\theta} = J^{+}\ddot{P} + \left(J^{+}\right)' \dot{P} \tag{12}$$

Substituting (9) into (12)

$$\begin{aligned} \ddot{\theta} &= J^{+}\ddot{P} + \left(J^{+}\right)' \dot{P} = J^{+}\ddot{P} + \left(\left(J^{T}J\right)^{-1} J^{T}\right)' \dot{P} \\ &= J^{+}\ddot{P} + \left(J^{-1}J^{-T}J^{T}\right)' \dot{P} = J^{+}\ddot{P} - \dot{J}\dot{P} \end{aligned} \tag{13}$$

Since J^{+} is the pseudo inverse matrix of J, based on the characteristic of the pseudo inverse matrix, one has

$$-\dot{J} = -J^{+}\dot{J}J^{+} \tag{14}$$

Substituting (14) into (13)

$$\begin{aligned}\ddot{\theta} &= J^{+}\ddot{P} - \dot{J}\dot{P} \\ &= J^{+}\ddot{P} - J^{+}\dot{J}J^{+}\dot{P} \\ &= J^{+}\left(\ddot{P} - \dot{J}J^{+}\dot{P}\right)\end{aligned} \tag{15}$$

Next, substituting $J^{+} = \left(J^{T}J\right)^{-1}J^{T}$ into (15)

$$\ddot{\theta} = J^{+}\left(\ddot{P} - \dot{J}J^{+}\dot{P}\right) = \left(J^{T}J\right)^{-1}J^{T}\left[\ddot{P} - \dot{J}(J^{T}J)^{-1}J^{T}\dot{P}\right] \tag{16}$$

where $\dot{P} = \begin{bmatrix}\dot{x} & \dot{y} & \dot{\varphi}\end{bmatrix}^{T}$.

With the above analysis

$$\begin{cases} e_i(t) = P_d - P \\ \dot{e}_i(t) = \dot{P}_d - \dot{P} \end{cases} \tag{17}$$

where P_d is the desired position vector, $e_i(t)$ is the position error, and $\dot{e}_i(t)$ is the time derivative of $e_i(t)$.

Thus, the control law $u_i(t)$ in the position control loop is designed as

$$\begin{aligned} u_i(t) &= K_P e_i(t) + K_I \int_0^t e_i(t)dt + K_D \dot{e}_i(t) \\ &= K_P\left(e_i(t) + \frac{1}{T_i}\int_0^t e_i(t)dt + T_D \dot{e}_i(t)\right) \end{aligned} \tag{18}$$

with

$$\begin{cases} K_I = \dfrac{K_P}{T_i} \\ K_D = K_P T_D \end{cases} \tag{19}$$

where $e_i(t)$ is the positive error vector in the position control loop, as shown in Fig. 2. K_P, K_I and K_D are the proportional parameter, integral parameter and differential parameter, respectively. T_I and T_D are the integral time and differential time, respectively. Note that the Ziegler-Nichols frequency response method [34] is used to adjust the parameters K_P, T_I and T_D in this section. Moreover, the transfer function of the control law (18) is described as

$$u_i(s) = \frac{K_P}{T_i}\frac{(s+a)(s+b)}{s} \tag{20}$$

with

$$\begin{cases} a = \dfrac{T_i}{2}\left(1 + \left(1 - \dfrac{4T_d}{T_i}\right)^{\frac{1}{2}}\right) \\ b = \dfrac{T_i}{2}\left(1 - \left(1 - \dfrac{4T_d}{T_i}\right)^{\frac{1}{2}}\right) \end{cases} \tag{21}$$

where a and b are the zero points of the polynomial $(s+a)(s+b)$ on the root locus plane. Proportional control can reduce the steady state error, but if the proportional parameter is too large, the stability of the system may be decreased. Integral control and differential control will improve the stability of closed-loop system. Thus, the PID controller based on the position control is designed in the position control loop for the fuzzy PI position/force hybrid control structure in this paper. Besides, the schematic diagram of the fuzzy PI position/force hybrid control is show in the Fig. 2.

3.2. Improved redundant force control structure

The control structure in this paper is position/force hybrid scheme [24]. The first five branches of 6PUS-UPU are adopted three loop control schemes. In practice, the PI control techniques often offer good performance [35, 36], so the speed loop and current loop adopt the PI control [25]. To keep the stiffness of system and rapid response, the position loop, in general, uses the P controller [37].

Because of the complexity of 6PUS-UPU in the control process, it is not easy to get a desired performance index under the environment with disturbances. The effective approach to solve this problem is fuzzy control [38-42]. In order to make the accuracy and tracking performance better under the environment with disturbances, we put forward a fuzzy PI force controller [43-46].

To make the performance simpler and more rapid, meanwhile, to ensure the accuracy of the mobile platform, the 6PUS-UPU's position branches use the following three-loop control scheme, that is, use the P controller for the position loop, use the PI controller respectively for the speed loop and current loop. Because of the complex 6PUS-UPU robot's structure, if all branches are used fuzzy control, it will lead to more time-consuming simulation experiments. In the hereafter research, we need to use a simplified structure to design the position of the branch controller. However, fuzzy PI force controller is designed in the force branch of 6PUS-UPU platform. Different from the first five branches, we apply the dynamic model [24] to get the inverse solution of driving force and this structure introduces the mobile platform's real-time pose variable [26].

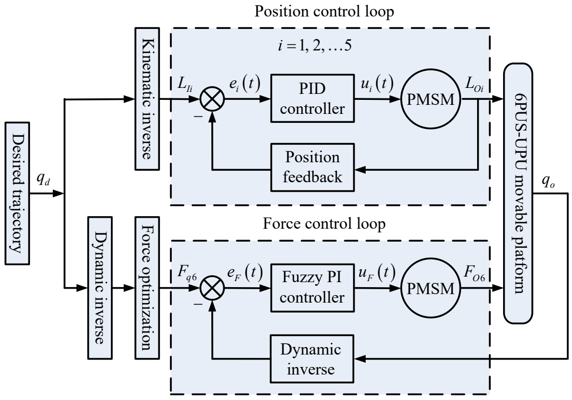


Fig. 2. Schematic diagram of the fuzzy PI position/force hybrid control.

3.3. Redundant force controller design

The active stiffness and the driving forces can be better handled by the redundant branch. However, because of the uncertainties and nonlinearities are connect to the redundant branch, the controller design of the 6PUS-UPU will become more complex.

Fuzzy control can be used in the system with delay and nonlinearity because it does not require the precise mathematical model, and can make the design processes simpler, as well can obtain good robustness. In the practical situation, the anti-interference ability can be deal because there exists uncertain interference. But conventional fuzzy controller cannot obtain ideal results, such as smaller steady state error. One of the efficient methods is connecting fuzzy control with PI controller. The redundant branch can use fuzzy PI controller.

Based on ref. [47], the redundant branch Fuzzy PI controller is designed as follows

$$\Delta u_F(t) = k_{\Delta u}\cdot F\left[k_e\cdot e_F(t),\ k_{ec}\cdot ec_F(t)\right] \tag{22}$$

where $e_F(t)$ is the force error vector in the force control loop, as shown in Fig. 2, $ec_F(t)$ is the differential of $e_F(t)$, $F[\bullet]$ represents a kind of mapping relationship based on the fuzzy inferential process [47, 48], and $k_{\Delta u}$ is the fuzzy proportional factor for $F[\bullet]$.

Based on ref. [47], the control law $u_F(t)$ in the force control loop is designed as follows.

$$u_F(t) = \int_0^t k_{\Delta u}\cdot F\left[k_e\cdot e_F(t), k_{ec}\cdot ec_F(t)\right]dt \tag{23}$$

where $E = k_e\cdot e_F(t)$ and $\dot{E} = k_{ec}\cdot ec_F(t)$. If $(E,\dot{E})\to(0,0)$, the equality (23) can be linearized.

The linearization results of equality (23) can be approximated as

$$\begin{aligned} F\left[k_e\cdot e_F(t), k_{ec}\cdot ec_F(t)\right] &= F\left[E,\dot{E}\right] \\ &= k_1 k_e e_F(t) + k_2 k_{ec} ec_F(t) \end{aligned} \tag{24}$$

where k_1 and k_2 are the scalars representing the linearization coefficients.

The equation (23) can be rewritten as follows

$$\begin{aligned} u_F(t) &= K_{FP} F\left[k_e\cdot e_F(t), k_{ec}\cdot ec_F(t)\right] \\ &+ K_{FI}\int_0^t F\left[k_e\cdot e_F(t), k_{ec}\cdot ec_F(t)\right]dt \end{aligned} \tag{25}$$

where K_{FP} is the proportional gain and K_{FI} is the integral gain. K_{FP} and K_{FI} are the regulating values in the fuzzy PI regulating process.

The equation (25) is the expression of fuzzy PI force controller in Fig. 3 the fuzzy PI output is $u_F(t)$ rather than $\Delta u_F(t)$. By adjusting the fuzzy PI regulating parameters K_{FP} and K_{FI}, the system can achieve a good control performance. The schematic diagram of the fuzzy PI force control is shown in Fig. 3.

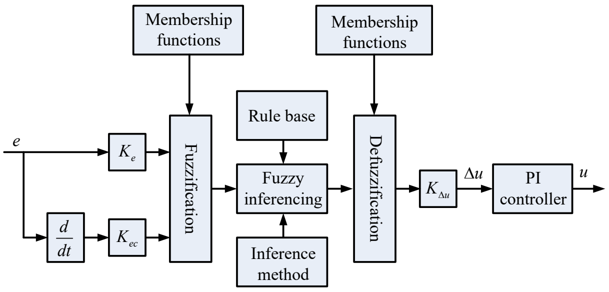


Fig. 3. Schematic diagram of the fuzzy PI force control.

The implementation of the fuzzy PI controller requires several parts, and they are quantization factors, fuzzification, rule base, inference engine and defuzzification. Next, we will briefly discuss these issues.

(i) Quantization factors: The fuzzy PI controller controls use standardized input and output variables, so the input variable needs to multiply quantization factors to map the universe of discourse in a range. In this paper, the range is $[-6,\ 6]$. The output of the basic fuzzy controller also needs to get the actual range which is $[-6,\ 6]$ by a denormalization factor.

(ii) Fuzzification: The inputs of the fuzzy controller are the error and the change rate of error. The outputs are the controller output, and they are crisp values. So they need to be mapped in linguistic variables. In this paper, E, EC, U are the input and output linguistic variables. Their fuzzy sets are [NB, NM, NS, Z, PS, PM, PB], which denote "negative big", "negative middle", "negative small", "zero", "positive small", "positive middle" and "positive big", respectively. Because of the characteristics of smooth non-zero at all points and nonlinear functions [49-51], Gaussian membership functions are used in this paper, which is shown in Fig. 4. Note that the lines “NB”, “NM”, “NS”, “ZO”, “PS”, “PM” and “PB” in Fig. 4 denote the membership functions for the rules “NB”, “NM”, “NS”, “ZO”, “PS”, “PM” and “PB”, respectively.

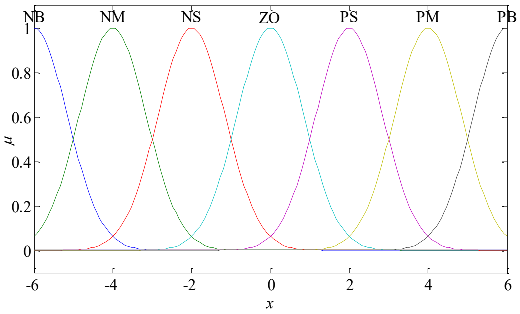


Fig. 4. Membership functions of the fuzzy rules.

(iii) Rulebase: The key of the fuzzy controller is rule base, and the key of rule base is the experience of experts. Fuzzy rules are shown in Table 1. It adopts the form of "IF-THEN" statements and logical "AND" operation as follows:

(1) IF E = NB AND EC = NB, THEN U= PB;
(2) IF E = NB AND EC = NM, THEN U= PB;
⋮
(49) IF E = PB AND EC = PB, THEN U= NB.

Table 1. Fuzzy rules of the fuzzy PI controller.

U EC E	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PM	PS	Z	Z	NS
Z	PM	PS	PS	Z	NS	NS	NM
PS	PS	Z	Z	NS	NM	NM	NB
PM	Z	Z	Z	NM	NM	NB	NB
PB	Z	NS	NS	NB	NB	NB	NB

(iv) Inference engine: An overall control action with reasoning method is provided according to the contribution of each rule in the rule base. we use a Mamdani-type fuzzy inference engine to provide the overall control action. The three-dimensional graph of e_F, ec_F and Δu_F is shown in Fig. 5.

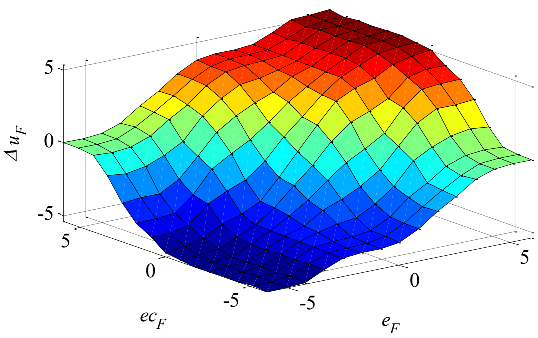


Fig. 5. Three-dimensional graph of e_F, ec_F and Δu_F.

(v) Defuzzification: The defuzzification is the opposite operator of fuzzification interface, and it turns the linguistic values of the output to a crisp value. The most popular defuzzification method is the center of gravity method, which can return the center of the area under the curve. In the paper, we use the center of gravity as the defuzzification method.

Remark 2. During the past decades, fuzzy control systems with heuristic knowledge or linguistic information provide an appealing and effective approach insensitive to the system parameters as well as to reduce the effects of unknown nonlinearities for the nonlinear control systems. Also, the fuzzy control can be applied to the controlled plants with unknown or unavailable mathematical model where it only can be controlled successfully by an operator with experience [41]. Thus, the fuzzy PI controller is designed in this paper to reduce the system uncertainties caused by the dynamic model.

3.4. Stability analysis of the redundant force controller

The stability analysis is always one of the most important problems. The linear approximation method is used to analyze the stability problem of nonlinear fuzzy controller in this paper. The linear approximation analysis method of fuzzy controller stability is as follows:

The controlled object is expressed by the state equation [52].

$$\begin{cases} \dot{X} = AX + Bu_F(t) \\ y = CX \end{cases} \tag{26}$$

where X is the state vector, A, B and C are the state matrix, control matrix and output matrix, respectively. We suppose that the output of fuzzy controller is used as nonlinear function of the inputs $e_F(t)$ and $ec_F(t)$.

$$u_F(t) = f\left(e_F(t), ec_F(t)\right) \tag{27}$$

Based on the linear approximation method, we can assume that there exist K_1 and K_2 to make the equation (27) hold. So equation (28) is used to replace equation (27).

$$u_F(t) = K_1 e_F(t) + K_2 ec_F(t) \tag{28}$$

If the reference output of the system is r, then

$$\begin{cases} e_F(t) = r - y = r - CX \\ ec_F(t) = -\dot{y} = -C\dot{X} \end{cases} \tag{29}$$

From (26)-(29), one has

$$\dot{X} = \left(I + K_2BC\right)^{-1}\left(A - K_1BC\right)X + \left(I + K_2BC\right)^{-1}BK_1r \tag{30}$$

The equation (30) can be simplified as

$$\dot{X} = \Phi X + X_0 \tag{31}$$

where

$$\begin{cases} \Phi = \left(I + K_2BC\right)^{-1}\left(A - K_1BC\right) \\ X_0 = \left(I + K_2BC\right)^{-1}BK_1r \end{cases}$$

The sufficient and necessary condition of the stability in equation (31) is that there exists a solution to the following equation [53, 54]

$$\Phi^T P + P\Phi = -Q \tag{32}$$

where P and Q are symmetric positive definite matrixes. The condition in equation (31) implies the existence of a set of K_1 and K_2 such that

$$\left\{ (K_1, K_2) \middle| F_i(K_1, K_2) = 0 \right\} \quad (i = 1,\ 2\ \ldots) \tag{33}$$

where $F_i(\bullet)$ is a kind of identified function [26]. Then we can choose a subset to satisfy the inequalities

$$\alpha_1 \le K_1 \le \alpha_2, \quad \beta_1 \le K_2 \le \beta_2 \tag{34}$$

Based on equation (34), we can get the range of the nonlinear expression equation (28) as follows

$$\alpha_1 e_F(t) + \beta_1 ec_F(t) \le u_F(t) \le \alpha_2 e_F(t) + \beta_2 ec_F(t) \tag{35}$$

The system is guaranteed to be stable when the above conditions are satisfied. In fact, as long as we could adjust the parameters and design the fuzzy rules reasonably, the whole system could be made stable.

Remark 3. Because of the numerous constraints imposed by closed-loop of the parallel manipulator, deriving explicit equations of motion in terms of a set of independent generalized coordinates becomes a prohibitive task. And the principle of force controller appears to be the better efficient method of analysis. Thus, the redundant force controller is designed in this paper.

4. SIMULATION RESULTS AND ANALYSIS

The reference trajectory of the platform is given as

$$\begin{tikzcd} (0, 0, 928) \arrow[r] & (-100, -11, 928) \arrow[d] & \text{(mm)} \\ (100, 100, 928) & (0, 0, 928) \arrow[l] & \end{tikzcd}$$

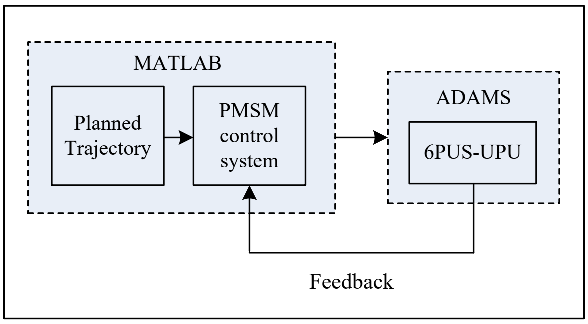
Based on the application of the 6PUS-UPU, position tracking banned from shocks and overshoots. So all DOFs are designed as damped and the damping ratio $\zeta_j >= 1$, i.e., $\zeta_j = 1$, $j = 1,\ 2,\ \cdots,\ 5$. Besides, the cut-off frequency W_j is 10π to get a short setting time. The redundant branch input can be computed by KANE equation. The main parameters are shown in Table 2 and Table 3. The using details of the parameters of 6PUS-UPU parallel robot are shown in [27].

Table 2. The parameters of the PMSM.

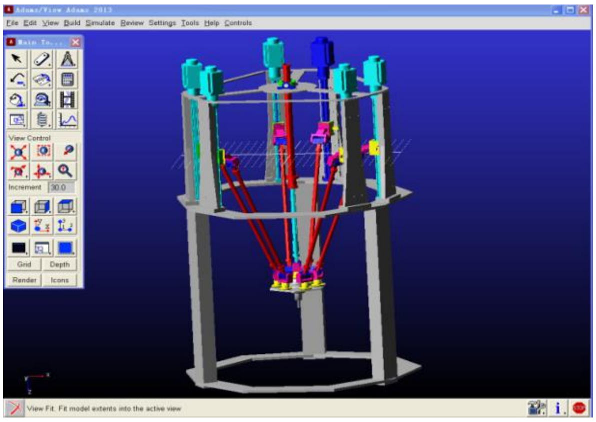
Parameter	Meaning	Value	Unit
L	rotator inductance	0.00027	H
R	rotator resistance	1.3	Ω
P_n	number of pairs	1	/
J	movement of initial	0.0062	$K_g \cdot m^2$
K_e	torque constant	0.167	/
τ_v	inverter time constant	0.0001	s
K_n	inverter gain	4.43	/
K_s	proportional coefficient	$5/\pi$	/

Table 3. Parameters of the fuzzy PI position/force hybrid control.

Parameter	Meaning	Value	Unit
K_P	proportional parameter of $u_i(t)$	15	/
K_I	integral parameter of $u_i(t)$	50	/
K_D	differential parameter of $u_i(t)$	1.5	/
T_I	integral time of $u_i(t)$	0.3	s
T_D	differential time of $u_i(t)$	0.1	s
k_e	quantification factor of e	0.1	/
k_{ec}	quantification factor of ec	0.17	/
$k_{\Delta u}$	quantification factor of Δu	0.75	/
K_{FP}	proportional parameter of fuzzy PI	0.65	/
K_{FI}	integral parameter of fuzzy PI	5.7	/

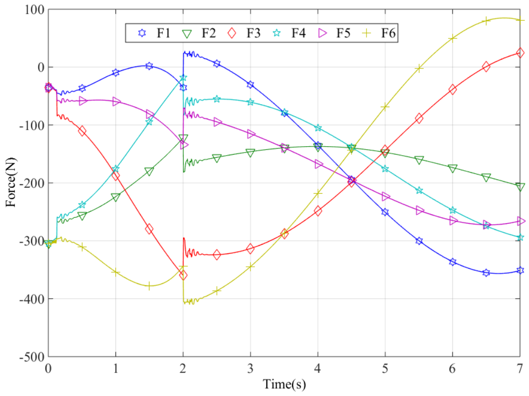


(a) simulation experiment diagram of the overall system

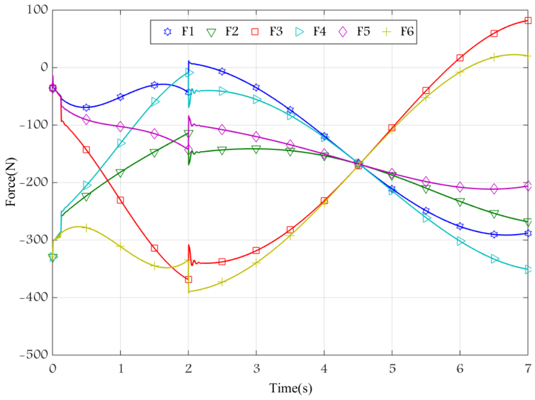


(b) virtual model of 6PUS-UPU

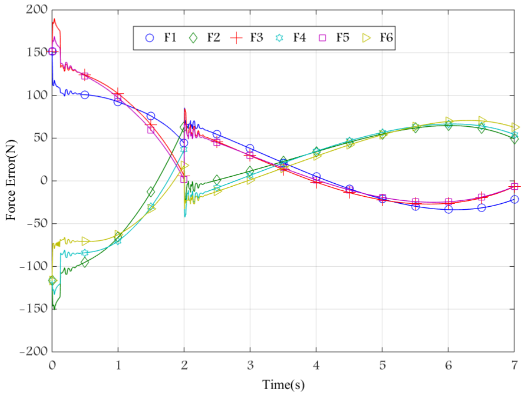
Fig. 6. Automatic dynamic analysis of mechanical systems (ADAMS) simulation experiment platform for 6PUS-UPU.



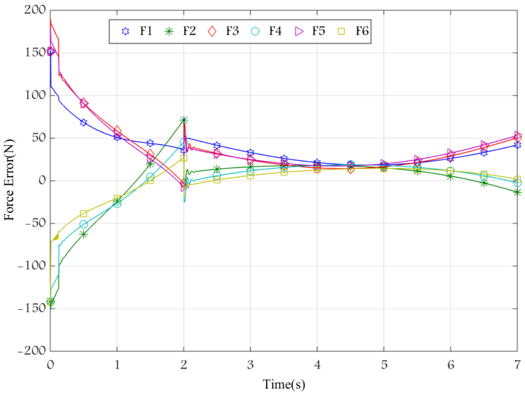
(a) Actual actuated force of the PI control scheme without interference



(b) Actual actuated force of the fuzzy PI control scheme without interference



(c) Force error of the PI control scheme without interference



(d) Force error of the fuzzy PI control scheme without interference

Fig. 7. Force tracking results of the PI and fuzzy PI controller.

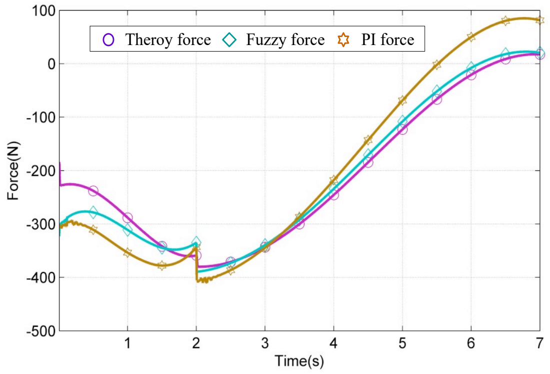
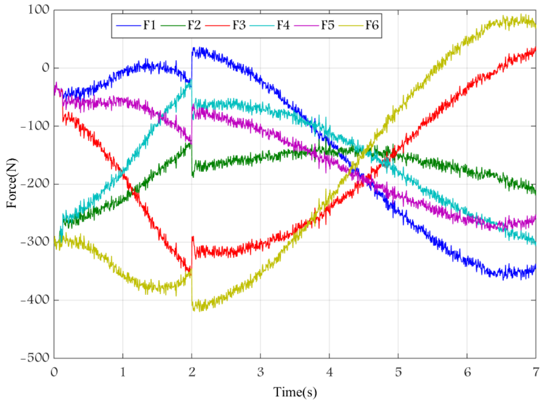
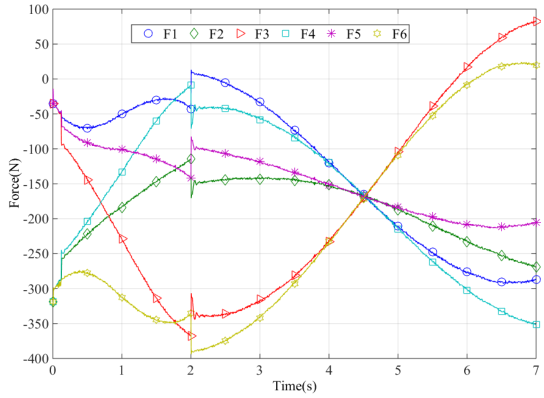


Fig. 8. Force of the sixth branch using the PI controller and fuzzy PI controller.



(a) actual driving forces of the PI controller with interference



(b) actual driving forces of the fuzzy PI controller with interference

Fig. 9. Results of the PI controller and fuzzy PI controller with interference.

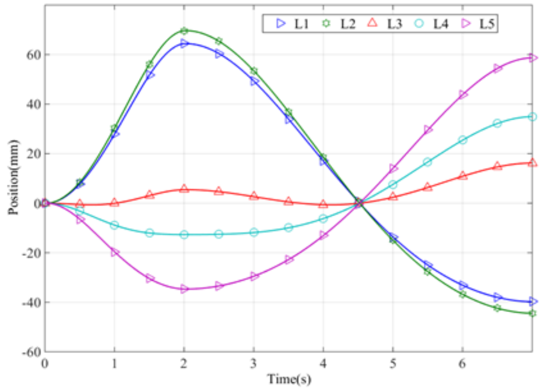


Fig. 10. Motions of position branches for the fuzzy PI control.

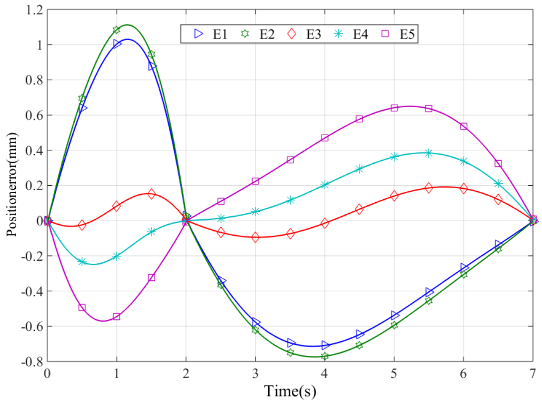


Fig. 11. Motion errors of position branches for the fuzzy PI control.

The automatic dynamic analysis of mechanical systems (ADAMS) simulation experiment platform for the 6PUS-UPU is shown in Fig. 6. The ADAMS simulation experiment software is the virtual prototype analysis software developed by the Mechanical Dynamics Company in American. The simulation experiment software of ADAMS can be used to predict the mechanical system performance, motion range, obstacle detections, peak load and input load of finite element method [55]. Firstly, the mechanical model of the 6PUS-UPU is analyzed, the virtual prototype model of the 6PUS-UPU is built via the ADAMS, and the control model of the 6PUS-UPU is built via the Simulink toolbox in the MATLAB in this paper. Secondly, the co-simulation model was achieved via the ADAMS/Control block and MATLAB/SIMULINK port, then the model accuracy is verified by using the real data of the 6PUS-UPU. Thirdly, the control system of the 6PUS-UPU is designed in the co-simulation experiment environment, and the performance of control system for the 6PUS-UPU is tested in this co-simulation experiment environment. Thus, the simulations experiment results, i.e., the Figs. 7-11 are presented for the 6PUS-UPU via the ADAMS simulation experiment platform. Moreover, the similar method can be found in [55].

The force tracking results of the PI and fuzzy PI controller without interference are shown in Fig. 7. From Fig. 7, we can see that because of combining movable platform pose with the dynamics, the force tracking capability under fuzzy PI control is better than the PI control under noise-free situation. The error is within 50N when the mechanism is stable and the PI control changes greatly. In Fig. 8, the fuzzy PI controller has less error of driving forces than that of PI controller. Next we will test the performance of the fuzzy PI controller and PI controller under interference, and the Gaussian noise is added into the redundant branch. Fig. 9 (a) and Fig. 9 (b) demonstrate that fuzzy PI controller can obtain better tracking performance than the PI controller with interference, and response curve of each branch is smooth.

From Fig. 10 and Fig. 11, it can be seen that the errors of the first five branches are smaller than 1.5 mm. It demonstrates that the proposed position/force hybrid control structure in this paper can provide good position tracking results.

5. CONCLUSION

This paper investigates the fuzzy position/force hybrid control for a class of 5-DOF redundantly actuated parallel robots. A novel concept, in which the movable platform pose error was introduced to the closed-loop control structure, has been proposed. The fuzzy PI control scheme is applied to achieve the optimal solutions for the 6PUS-UPU redundantly actuated parallel robot. The obtained results have expressed that the approach demonstrates improvement in the tracking performance and position tracking performance of driving forces compared to PI control scheme without the system model. Finally, the co-simulation experiment results of ADAMS and MATLAB/SIMULINK are given to show the effectiveness of the proposed methods compared with the conventional PI controller. Future study is to design the better position structure of the redundant actuation parallel robot in the presented framework.

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