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CMAC-based compound control of hydraulically driven 6-DOF parallel manipulator †

Shou-Kun Wang*, Jun-Zheng Wang and Da-Wei Shi
School of Automation, Beijing Institute of Technology, Beijing 100081, China

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Abstract

The movement precision of the hydraulically driven 6-six degrees of freedom (6-DOF) parallel manipulator is determined mainly by the precision of the valve-controlled asymmetrical cylinder (VCAC). Unfortunately, the asymmetrical movement of the VCAC caused by its asymmetrical structure can significantly compromise control precision. Owing to this asymmetry and, more fundamentally, the inherent nonlinearity of hydraulic systems as well as complicated load variations, it is very difficult to achieve ideal control precision with traditional (PID) control. In the present study, the working principle and characteristics of VCAC were analyzed, with particular focus on the asymmetry problem. In order to improve the precision of both VCAC control and 6-DOF parallel manipulator movement, this paper presents a new, cerebellar model articulation control (CMAC)-based control method. Experiments on both the single VCAC system and the parallel manipulator were developed to verify the validity and effectiveness of the new compound control method. The theoretical analysis and testing results, compared with those for the PID control, proved that the proposed CMAC-based control method can acquire high movement precision on the 6-DOF motion simulator while eliminating the need to build a mathematical model or obtain accurate loading conditions.

Keywords: 6-DOF parallel manipulator; Asymmetry; Cerebellar model articulation control; Compound control; Valve-controlled asymmetrical cylinder

1. Introduction

The advantages of the parallel-type robot over the tandem-type include strong stiffness, heavy loading capability and high control precision, all of which have made it a hot topic in the robot research field for almost forty years. One of its most important applications, the hydraulically driven six degrees of freedom (6-DOF) parallel manipulator, has favorable prospects and an overall high potential [1]. The manipulator typically comprises an upper platform, a basement, upper hinges, lower hinges, and six sets of electro-hydraulic servo systems that connect the upper platform with the basement. Fig. 1 shows a hydraulically driven 6-DOF parallel manipulator with a Steward structure developed by the Beijing Institute of Technology. The coordinated control of six valve-controlled asymmetrical cylinder (VCAC) position servo systems drives the upper platform of the manipulator to impart 6-DOF movement. Fig. 2 offers a schematic representation of the control structure of the manipulator.

The 6-DOF parallel manipulator shown in Fig. 1 without attitude sensors is an open-loop control system. Its precision is determined mainly by that of each VCAC. Due to the inherent nonlinearity of hydraulic systems [2], complicated load variations and, not least, the asymmetry of the VCAC itself, which reflects the asymmetrical structure of the cylinder [3], it is very difficult to achieve with traditional PID control to achieve ideal VCAC control performance [4]. To solve this control problem for hydraulically driven 6-DOF parallel manipulators incorporating VCAC, this paper proposes a new, cerebellar model articulation control (CMAC)-based compound control method.

When controlling hydraulically driven multiple-DOF parallel manipulators, each system is often considered to be independent and uncoupled [5, 6], with the couplings between joints being treated as factors of disturbance and indeterminacy [7]; therefore, controller design pertaining to the multiple-DOF parallel manipulator can be converted into single controller design for each VCAC system. Intelligent control methods for hydraulically driven 6-DOF parallel manipulators have always been the objects of great attention. In recent years, several advanced control methods have been developed, including self-adaptive control, robust control, sliding-mode control, and others.

Kim and Lee [8] have designed a kind of robust controller

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*Corresponding author. Tel.: +8268912465 203, Fax.: +8268912465 210
E-mail address: bitwsk@bit.edu.cn

Fig. 1. Hydraulically driven 6-DOF parallel manipulator developed by the Beijing Institute of Technology.

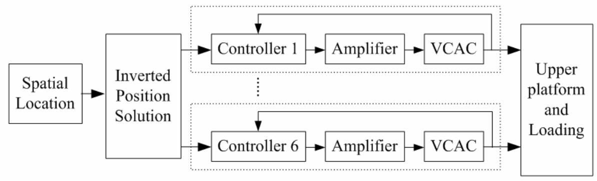


Fig. 2. Control structure of the hydraulically driven 6-DOF parallel manipulator.

based on the PD control structure, which can output different nonlinear compensation according to specific working conditions. Wan et al. [9] have developed a new dynamic neural network by adding a feedback link to the feed-forward net, and derived a fast self-study algorithm. Meanwhile, Yuan et al. [10] have presented a compound controller incorporating both PID control and wavelet network control for on-line, real-time control by way of dynamics compensation. Lee et al. [11] have designed a control method based on a $H\infty$ controller and a dynamic model, and demonstrated its superiority to PID control. Fu et al. [12] have designed an nonlinear, robust controller after the friction characteristics of a single channel of the 6-DOF parallel manipulator, and conducted a simulation validating its effectiveness. Han and Chang [13] have designed an enhanced controller to improve the robustness of time delay control (TDC) for a robot manipulator in the presence of nonlinear friction. Khaloozadeh and Homaeinejad [14] have developed a chattering avoidance sliding mode controller for space free-flying robots as highly nonlinear-coupled systems. In their work, IIwatsuki et al. [15] have described the position and stiffness control of planar redundant link mechanisms with elastic elements in order to utilize the flexibility of robots. Moreno-Valenzuela and Orowo-Manriquez [16] have introduced a control scheme based on using a using a trajectory tracking controller and an algorithm for on-line time-scaling of the reference trajectories. Kang [17] has designed a variable structure fuzzy control method and a switching logic to eliminate the steady-state tracking errors. These control methods, however, are all limited in practical applications to some extent, owing to real-time response or dependence on model building.

Cerebellar model articulation control (CMAC) is a new type of neural network first advanced by Albus [18]. It is a local-learning-based control, which is very suitable for real-time control of the servo control system, with its simple network structure, high convergence precision and rapid learning speed [19]. CMAC has been applied in many research fields, including function approach, dynamic modeling, pattern recognition and others; it has provided a new solution to the problem of VCAC control design as well.

In the present study, the working principle and characteristics of VCAC were analyzed, and a new compound control method and CMAC-based controller were derived to improve the control precision of both the single VCAC system and the 6-DOF parallel manipulator. The results of the experiments proved that it can achieve ideal VCAC control while eliminating the need to build a mathematic model or obtain accurate loading conditions thereby.

2. Principle and characteristics of VCAC

The asymmetrical cylinder with a single pole, compared with the symmetrical cylinder with two poles, has many advantages in industrial applications, including a compact working space, a simple structure, its ease of production and its reliably oil-proof condition, among others [20]. However, the working characteristics of VCAC are much different from those of the valve-controlled symmetrical cylinder, due to the structural asymmetry. Simply speaking, the VCAC characteristics of motion for one direction are not the same as those for the other. Fig. 3 illustrates the VCAC structure, where input x_v is the displacement of the valve core; y is the displacement of the piston; A_1 and A_2 are the piston areas of the two sides ($\eta = A_2 / A_1 < 1$), respectively; p_1 and p_2 are the respective pressures in the two cavities of the cylinder; p_s is the oil-supply pressure; and p_0 is that of the oil return. If $\dot{y} > 0$, the movement is positive, indicating cylinder extension, and if $\dot{y} < 0$, the movement is negative, indicating cylinder retraction.

After analyzing the loading flow characteristics of VCAC, ignoring elastic and damped loading, a mathematical model could be derived according to some simplified representations, which can be expressed as Eq. (1):

$$Y(s) = \frac{\dfrac{K_q}{A_1} x_v(s) - \dfrac{C_t}{A_1} p_s - \dfrac{K_{ce}}{A_1^2}\left(\dfrac{V}{\left(1+\sqrt{\eta}\right)^2 \beta_e K_{ce}} s + 1\right) F(s)}{s\left(\dfrac{s^2}{\omega_h^2} + \dfrac{2\zeta_h}{\omega_h} s + 1\right)} \tag{1}$$

where ω_h is the frequency of the cylinder, ζ_h is the hydraulic damping coefficient, K_q is the flow gain of the valve in the zero position, K_{ce} is the flow-pressure coefficient, C_t is the leakage rate of the cylinder, and β_e is the effective modulus of volume elasticity.

The values of K_q , K_{ce}, C_t , and ζ_h in positive movement are much different from those in the negative movement,

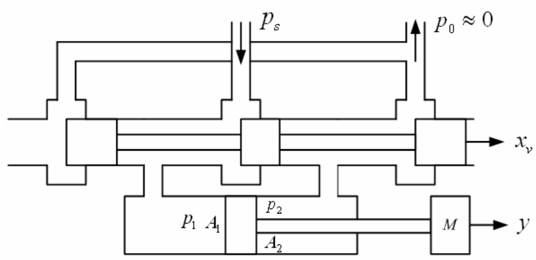


Fig. 3. Structure of the valve-controlled asymmetrical cylinder.

given, again, the asymmetrical structure of the cylinder. Among these parameters, the variation of K_q can have a significant influence on the dynamic performance of VCAC. Eq. (2) defines K_q for both positive and negative movements, where C_d and w are the throttle coefficient and valve area, respectively, ρ is the oil density, and p_L ($p_L = p_1 - \eta p_2$) is the loading pressure. Under the no-load ($p_L = 0$) condition, $K_q^+ / K_q^- = 1/\sqrt{\eta} > 1$, which means that the dynamic response and tracing performance in positive movement are much better than those in the negative movement.

$$K_q = \begin{cases} K_q^+ = C_d w \sqrt{\dfrac{2}{\rho}\left(\dfrac{p_s - p_L}{1+\eta^3}\right)} & \dot{y} > 0 \\ K_q^- = C_d w \sqrt{\dfrac{2}{\rho}\left(\dfrac{\eta p_s + p_L}{1+\eta^3}\right)} & \dot{y} < 0 \end{cases} \tag{2}$$

The degree of asymmetry α is the degree of difference between positive movement and negative movement. It is very difficult to obtain a precise expression of α, which is determined mainly by η and p_L, among others, and is closely related to movement amplitude and frequency. When VCAC is applied to the position servo system, Eq. (3) can be used to calculate α based on the position error expressed as:

$$\alpha = \frac{2 \times \left(e^+ - e^-\right)}{\left(e^+ + e^-\right)} \times 100\% \tag{3}$$

where e^+ and e^- represent the positive and negative position errors, respectively.

The asymmetrical movement of VCAC caused by its asymmetrical structure has a great influence on control precision; indeed, it is very difficult to achieve ideal control with traditional PID. Thankfully however, the CMAC neural network has provided a feasible solution for control of severely asymmetrical VCAC.

3. Principle and structure of CMAC

CMAC is a kind of local-learning-based, self-adapting neural network that utilizes a look-up table [21] to express complex and nonlinear functions. Moreover, CMAC can automatically change the content of the table by means of its learning algorithm, providing a nonlinear mapping ability from input to output [22]. All of these attributes make CMAC especially applicable to the VCAC control problem. The mathematical principle and structure of CMAC can be described by the $S \to M \to A \to Y$ serial mapping displayed by Fig. 4, where S is the combined total input vectors, including $S_1, S_2 \cdots S_n$; M represents the space of concept storage; A is the space of actual storage; and $f(s)$ is the network output.

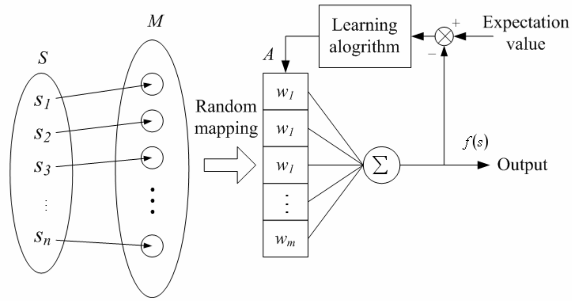


Fig. 4. Principle and structure of CMAC.

The principle of CMAC can be described by a series of working procedures. Every vector in input state space S, as an address variable, is mapped into concept storage M by means of rolling combination; the vectors adjacent to S are also contiguous in M. In other words, there is an associative relationship between S and M that can be measured by the number of associative elements expressed as C. Under the condition of a small number of input vectors, the addresses of the vectors in concept storage M are the same as those in actual storage A, but with growth in the number of input vectors; in addition, the size of A can become huge. Thus, pseudo-random mapping methods, such as Hash encoding that can map a huge storage M into a much smaller storage A with the same value of C, are often employed to reduce the size of storage space. However, with a small number of inputs, as was the case in the present study, A and M can be united in the same storage space. The final output of CMAC is the sum of the weights owned by C elements, and the weights stored in A are adjusted by a learning algorithm, which often uses gradient descent calculation to accelerate the learning process [23].

CMAC is based on high-speed local learning, making it very suitable for real-time control. It also possesses a generalization ability, which means that adjacent inputs generate identical outputs and different inputs generate diverse outputs. Furthermore, as a nonlinear approximation, CMAC is not sensitive to the sequence of learning samples [24, 25]. Considering its overall characteristics, which are excellent for nonlinear and real-time control, CMAC approximation is superior to that of other neural networks.

4. CMAC-based compound control

To restate, CMAC provides a feasible solution for control

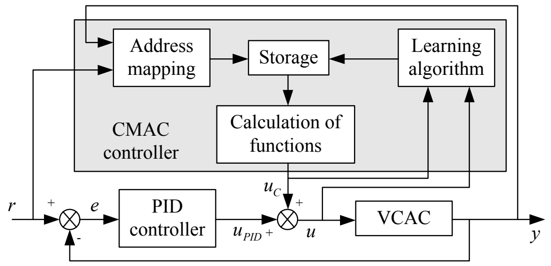


Fig. 5. Structure of the CMAC-based compound control.

of severely asymmetrical VCAC. The structure of a CMAC-based compound controller is schematized in Fig. 5, where r is the expected input; y is the actual output; e and $\dot{e}$ are the control error and error derivatives respectively; u_c is the CMAC controller output; u_{PID} is the PID controller output; and u is the total VCAC input.

Since input r and output y are all inputted into the CMAC controller as training signals for the adjustment of weights, CMAC controller contains not only the inverse model of VCAC, but also the inverse model of the whole system, including VCAC and PID controller. Thus, CMAC-based compound control is helpful in overcoming the asymmetry of the VCAC model and in improving the asymmetry and tracking accuracy in movement.

As Fig. 5 shows, the CMAC controller is configured in parallel with a PID controller, generating a kind of compound control. The PID controller provides learning samples to the CMAC controller in the initial stage or under loading variation conditions. At the same time, it plays a subsidiary control function. With system input r and system output y as inputs, the CMAC controller can adjust the weights dynamically using a learning algorithm. The working procedure of the CMAC controller, including learning and control, can be described as follows:

The weights are set to zero; accordingly u_c is zero, and the CMAC controller does not provide any control function.

System input r and system output y are inputted into CMAC after quantization. The state space of the input is divided in a fuzzification process, and the corresponding degree of membership can be calculated.

After determining the number of addresses C according to the inputs, the CMAC output u_c is calculated by adding the weights stored in the C elements.

The final VCAC input can be obtained by adding the outputs of the PID and CMAC controllers, $u = u_c + u_{PID}$.

In every control cycle, the weights are adjusted by comparing u_c with u and making the difference between them as small as possible; this adjustment is called the learning process. Then, after a number of learning cycles, the VCAC input is generated mainly by the CMAC controller. The learning algorithm can be described by Eqs. (4)-(6) expressed as:

$$J(k) = \frac{1}{2}\left(u_c(k) - u(k)\right)^2 \frac{1}{C} \tag{4}$$

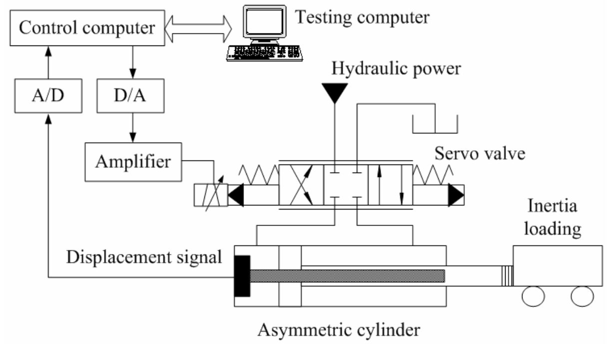


Fig. 6. Testing principle of the experimental system.

Fig. 7. Actual experimental equipment.

$$\Delta w(k) = \eta\left(1 - e^{-a|u_c(k)-u(k)|}\right)\frac{u_c(k) - u(k)}{C} \quad \eta \in (0,1) \text{ , and} \tag{5}$$

$$w(k) = w(k-1) + \Delta w(k) . \tag{6}$$

In Eqs. (4)-(6), J is the assessment index function, which should be as small as possible, and $\eta(1 - e^{-a|u_c(k)-u(k)|})$ is the learning rate of the network, where η is a small constant and $1 - e^{-a|u_c(k)-u(k)|}$ is the variation factor of the learning rate. As reduction of $|u_c(k) - u(k)|$, the learning rate of the network can decay by exponent regularity. When $|u_c(k) - u(k)|$ is smaller, a lower learning rate can reduce vibration and increase stability, whereas a bigger learning rate can accelerate the convergence procedure when $|u_c(k) - u(k)|$ is larger. a is a balance constant, which is designed for the coordination of the stability and convergence speed in learning procedure.

5. Experiments on single VCAC

In order to verify the CMAC-based compound control method, experiments on a single VCAC position servo system were carried out. Fig. 6 illustrates the testing principle of the experimental system, and a photograph of the experimental equipment is provided in Fig. 7.

The experimental system comprised a VCAC, including a servo valve and servo cylinder of asymmetrical structure, a control computer, a hydraulic power system, inertia loading, and other components. The stroke of the cylinder was 200 mm, the diameter of the piston was 50 mm, and the diameter of the

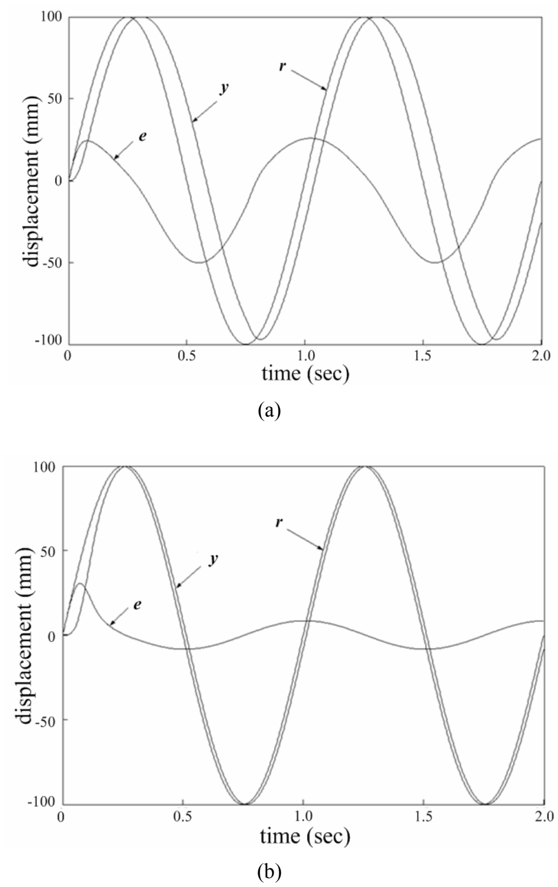


Fig. 8. Testing results for VCAC under fixed loading (a) PID controller; (b) CMAC-based compound controller.

pole was 36 mm. A 0.1% precision magnetostrictive displacement sensor was installed in the pole of the cylinder to measure the output of the VCAC. The servo valve, with 100 L/min rated flow, can work under 21 MPa oil pressure. The charger, an inertial trolly, can change the VCAC loading state by placing different mass blocks.

The control computer, a 100 MHz 486 CPU of PC-104 bus structure with 16 bit A/D, 16 bit D/A and a servo amplifier, operated in control cycles of less than 0.5 ms. A testing computer, connected with the control computer by Ethernet and TCP/IP, set the regularity of movement, sent control commands, and received and displayed testing data.

For the experiments, the oil pressure was set to 14 MPa, the inertial load was changed from 200 to 800 kg, the moving amplitude of the cylinder was 100 mm, the frequency was 1 Hz, and the movement regularity was:

$$y = 100\sin(2\pi t). \quad (7)$$

The CMAC-based compound controller and the traditional PID controller were tested under the same parameters to compare the effects of different control methods. Fig. 8 plots the results for the traditional PID controller and CMAC-based compound controller under fixed loading of 300 kg. The results for the PID controller shown in Fig. 8(a) were not ideal; the tracking error reached 40 mm, and the degree of asymmetry α, as calculated by Eq. (3), was more than 50%. As shown in Fig. 8(b), the control of the compound controller was not better than that of the PID controller at the initial stage. This is because the weights in CMAC were zero and consequently, their adjustment required a learning process. After about 200 control cycles, however, the compound controller achieved the ideal control precision with less than 10 mm of control error and a 10% degree of asymmetry.

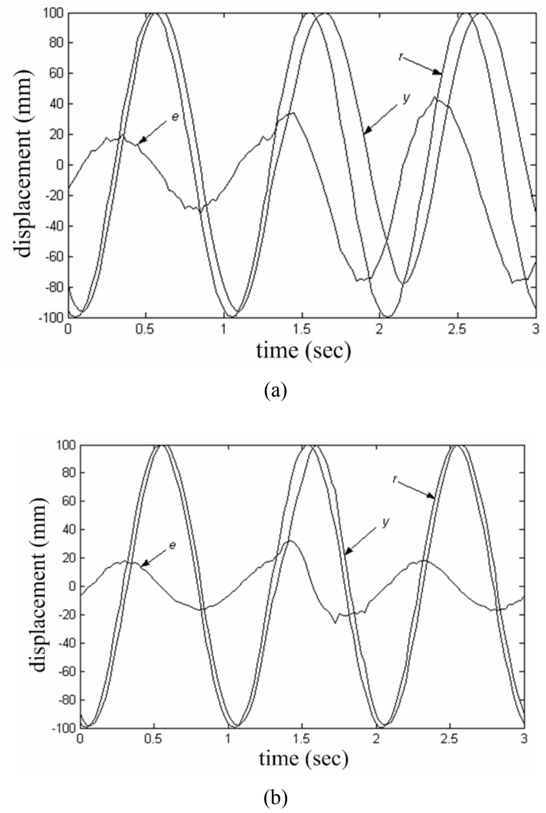
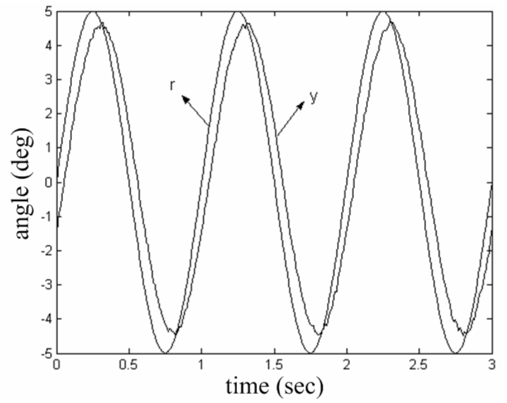


Fig. 9. Testing results for VCAC under variable loading (a) PID controller; (b) CMAC-based compound controller.

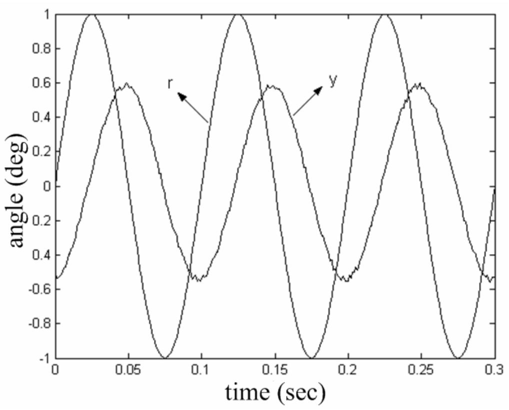
Generally, in the 6-DOF parallel manipulator, control precision is often affected by severe changing load; thus, the control effects of CMAC-based compound controller and the traditional PID controller for VCAC under variable loading have also been studied. Fig. 9 plots the results for the traditional PID controller and CMAC-based compound controller under variable loading, which changed from 200 to 800kg at time of 1.25s. The precision and the symmetry of PID controller were very sensitive to variable loading (Fig. 9(a)). In comparison, results for the CMAC-based compound controller were more ideal; the variable loading control error, which has been increased by mutational loading, was reduced rapidly by CMAC-based compound controller after fast study, and the precision and the symmetry was kept stable even under variable loading (Fig. 9(b)).

Table 1. Parameters and results of sinusoidal rotation around the X axis using PID control.

Amplitude /°	Frequency /Hz	Amplitude Error /%	Phase Error /°
10	0.5	2.5	12
5	1	10.2	21
2	5	23.4	35
1	10	44.7	83



(a)

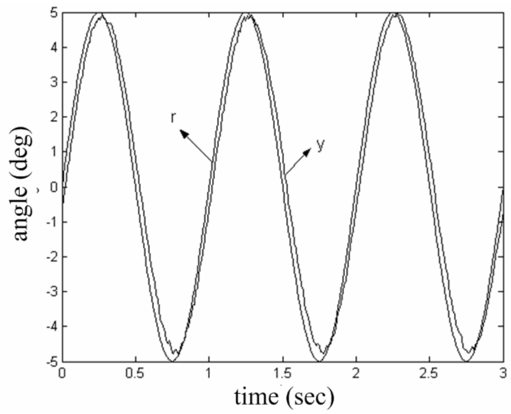


(b)

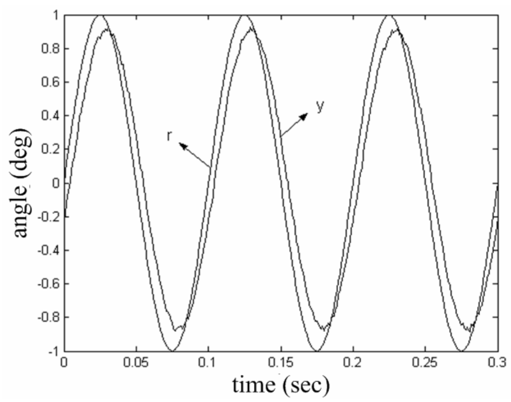
Fig. 10. Trial curves for PID control in experiments on the 6-DOF parallel manipulator (a) frequency is 1 Hz and amplitude is 5°; (b) frequency is 10 Hz and amplitude is 1°.

Table 2. Parameters and results of sinusoidal rotation around the X axis using CMAC-based compound control.

Amplitude /°	Frequency /Hz	Amplitude Error /%	Phase Error /°
10	0.5	2.5	5
5	1	3.7	9
2	5	6.6	12
1	10	11.8	16



(a)



(b)

Fig. 11. Trial curves for CMAC-based compound control in experiments on 6-DOF parallel manipulator (a) frequency is 1 Hz and amplitude is 5°; (b) frequency is 10 Hz and amplitude is 1°.

6. Experiments on 6-DOF parallel manipulator

Since the 6-DOF parallel manipulator displayed in Fig. 1 is an open-loop control system without attitude feedback, a fiber optic gyroscope was mounted on the manipulator's upper platform in order to obtain its actual attitude. The output of the gyroscope was used only to measure the controls of the different control methods; it was not incorporated into the control procedure. In the experiments, sine signals of differing frequency and amplitude were inserted into the manipulator to drive the upper platform's rotation around the X axis. The respective sets of testing parameters were 0.5 Hz and 10°, 1 Hz and 5°, 5 Hz and 2°, and 10 Hz and 1°.

The results for common PID control are listed in Table 1, and in Fig. 10, two of the corresponding trial curves are plotted, where curve *r* is the input and curve *y* is the output. These data showed that the PID control performance was not ideal, least of all for high-frequency motion. Once the input frequency reached 10 Hz, the amplitude error had grown to 44.7%, and the phase error had reached 83°. In this case, the output was seriously distorted relative to the input signal, because the degrees of amplitude decay and phase delay were so severe.

Table 2 lists the performance measures for CMAC-based compound control; two of the corresponding trial curves are plotted in Fig. 11, where curve *r* is the input and curve *y* is the output. It is clear that the compound control achieved much better results compared with common PID control. Even when the input frequency was as high as 10 Hz, the amplitude error was only 11.8%, and the phase error was just 16°. By means of the CMAC-based compound control, the output signal was able to track the input signal with a much higher degree of accuracy.

7. Conclusions

The movement precision of the hydraulically driven 6-DOF parallel manipulator is determined mainly by the control precision of VCAC. However, the VCAC's asymmetrical movement in different moving directions, as caused by its asymmetrical structure, can greatly affect control precision (i.e., the parameters in its mathematical model, especially flow gain K_q, can be significantly different for the different directions, positive and negative). Due to the asymmetrical structure of the VCAC, it is very difficult to achieve the ideal results with traditional PID control.

CMAC, which is based on high-speed local learning, presents a feasible solution for control of severely asymmetrical VCAC and satisfies the requirements of nonlinear and real-time control. Therefore, a new, CMAC-based compound control method has been proposed, according to which a CMAC-based compound controller is designed to improve the movement precision of the 6-DOF parallel manipulator driven by 6 sets of VCAC. Experiments on both the single VCAC system and the parallel manipulator have verified the validity and effectiveness of the new compound control method. The theoretical analysis and testing results showed that the new, CMAC-based control method, relative to PID control, can attain high movement precision with the 6-DOF parallel manipulator while eliminating the need to build a mathematical model or obtain accurate loading conditions.

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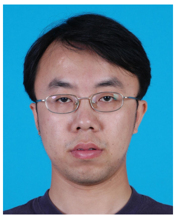

Shou-Kun Wang received his undergraduate, graduate, and doctorate degrees from the Beijing Institute of Technology from 1995 to 2004. He has been teaching at the School of Automation of the Beijing Institute of Technology since 2004. His research interests include sensor, measurement, and electro-hydraulic control. He has served participated in over 30 scientific research projects since 2001, which mainly belong to measurement and servo control. He has also served as the leader in some of these works. His main work has focused on control algorithm, data processing, and software programming.