Study on Variable Impedance Control of Hydraulic Manipulator Based on Double-Weighting-Factor Fuzzy Controller

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Study on Variable Impedance Control of Hydraulic Manipulator Based on Double-Weighting-Factor Fuzzy Controller

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Abstract. To improve the force control and position control performance of the hydraulic series manipulator, the author presents a double-weighting-factor fuzzy variable impedance control method, in order to have the manipulator end track the expected force along the environmental surface. Based on the dynamic model of the three-degree-of-freedom hydraulic series manipulator, the contact space and free space of the impedance control are analysed. A fuzzy controller is designed while supposing that the environmental information is known, to get B_d and K_d adjusted. Considering the time-varying characteristics of the system, a fuzzy controller with double weighting factors is designed to enhance the self-adjusting capability and the performance of the fuzzy controller. The simulation result shows that the proposed method achieves a good tracking control of force and position when the environmental parameters are time-varying.

1. Introduction

As hydraulic series manipulators become more and more widely used, people are getting more and more demanding on their degree of intelligence. The position control only can no longer satisfy the demands of complex applications. Especially when manipulator performs the environment-contacting tasks such as mounting and dismounting, grinding, man-machine collaboration and so on, a high requirement is raised both on the position control performance and the force control performance of manipulator. When the constraint relationship of the environmental surface that the manipulator end contacts is unknown, it is necessary to estimate the constraint relationship of the unknown environment by means of force-sensing information, vision-sensing information and so on.

Impedance control is, by setting up a dynamic relational model for the end acting force and the position, to select suitable model parameters, have a balanced control of force and position in the same frame, and use the same control strategy. Ficuciello et al. proposed a parameter-variable impedance control method for the redundant manipulator, and proved the effectiveness of the algorithm with the motion trail of man-machine collaboration[1]. To increase human force, Lecours et al. presented a variable impedance control method, in which the operator's intention is judged based on speed and acceleration, thus to change impedance parameters so as to improve operator's capability of carrying weights[2]. Based on the movement of digging opportunity in the free space and constrained space, Ying

Xu applied the switching function for sliding-mode control to impedance control, thus achieving the control of both position and force of manipulator[3].

Combining the situation of force / position control technologies, and based on the dynamic model of three-degree-of-freedom manipulator, the author used the double-weighting-factor fuzzy algorithm to optimize the impedance control, so as to provide a good compliance for the manipulator and to achieve an effective control of the environmental surface contacting force.

2. Dynamic model of hydraulic manipulator

Figure 1 shows the three-degree-of-freedom hydraulic series manipulator. Suppose the fourth degree of freedom is fixed.

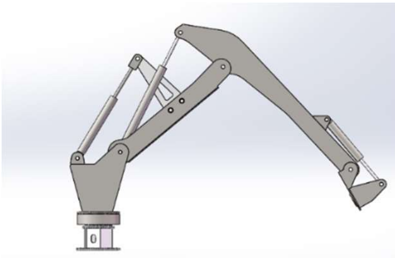

Figure 1. 3D model of hydraulic series manipulator

The dynamic model of manipulator is created by the lagrange method, and is expressed with the second-order nonlinear differential equation [4].

$$\boldsymbol{H}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{G}(\boldsymbol{q}) = \boldsymbol{\tau} + \boldsymbol{J}^T \boldsymbol{F}_{ext} \tag{1}$$

In this formula, H(q) is the 3×3 inertia matrix, $\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is 3×3 Coriolis/Centripetal matrix, $\boldsymbol{G(q)}$ is the 3×1 gravitational vector, $\boldsymbol{\tau}$ is the 3×1 joint-driving vector, $\boldsymbol{F}_{ext}$ is 3×1 force / torque vector applied on the end-effector of manipulator, and $\boldsymbol{J}^T$ is the Jacobin matrix. The details are shown as follows.

$$\begin{gathered}
\boldsymbol{H}(\boldsymbol{q}) = h_{ij} = \sum_{i=\max\{j,k\}}^{n} Trace\left(\frac{\partial^0 \boldsymbol{A}_i}{\partial \boldsymbol{q}_j} \boldsymbol{I}_i \frac{\partial (^0\boldsymbol{A}_i)^T}{\partial \boldsymbol{q}_k} \right) \\
\boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}}) = c_{ij} = \sum_{k=1}^{n} \frac{1}{2} \left(\frac{\partial h_{ij}}{\partial \boldsymbol{q}_k} + \frac{\partial h_{ik}}{\partial \boldsymbol{q}_j} - \frac{\partial h_{jk}}{\partial \boldsymbol{q}_i} \right) \dot{\boldsymbol{q}}_k \\
\boldsymbol{G}(\boldsymbol{q}) = g_i = -\sum_{j=1}^{n} m_j \bar{\boldsymbol{g}}^T \frac{\partial^0 \boldsymbol{A}_j}{\partial \boldsymbol{q}_i} {}^j\tilde{\boldsymbol{r}}_{Cj}
\end{gathered} \tag{2}$$

MATLAB is used to program the lagrange equation, which saves a large amount of calculation resulted in by manual deduction of dynamic equation. The elements, which will not be provided here, will be reserved after the program operation.

3. Double-weighting-factor fuzzy variable impedance control

3.1. Impedance Control

The impedance control based on inner position loop is applied to the force / position control of the manipulator. According to the acting force detected by the force sensor mounted at the end of manipulator, the position offset is generated by the outer-loop impedance control. Then the position offset and the manipulator's reference position are summated, and the inverse kinematics is done. Then the summation of the result obtained and the current actual angular position is made as the input of the inner-loop position controller, to achieve the track of expected position. With the help of the force sensor mounted at the end of manipulator, the acting force between the grinding head and the environment can be detected and converted into position offset e. According to the impedance control, we get the following result [5].

$$F_d - F = M_d\ddot{e} + B_d\dot{e} + K_d e \tag{3}$$

After converting it to frequency domain, we get the result that:

$$e(s) = \frac{F_d(s) - F(s)}{M_d s^2 + B_d s + K_d} \tag{4}$$

Formula (4) is equivalent to a low-pass filter. It makes low-pass filtration for each element in F(s) to obtain the position offset e. By summating this position offset and the reference position vector Xr generated by trajectory planning, we can get the next instruction location of position control.

$$X_c = X_r + e \tag{5}$$

If the manipulator moves in a free space and F=0, we get the result that e=0 and $\boldsymbol{X_r}$=$\boldsymbol{X_c}$. When the tool end of manipulator contacts the environment, and supposing that the position controller is precise enough, we get the result that $\boldsymbol{X}$=$\boldsymbol{X_c}$ and e=X-X_r . The impedance control can be expressed as shown in Figure 2.

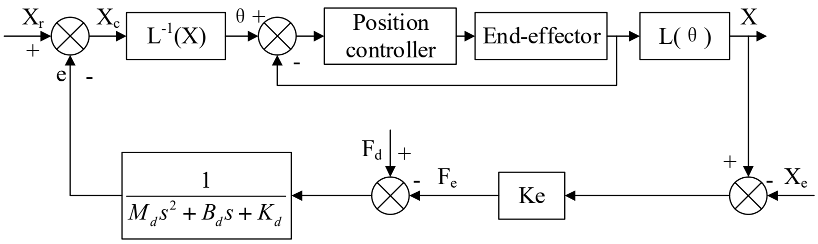

Figure 2. Model for impedance control

When the system makes free movement and has no contact with the environment, we get the result that F=0. At this time, the model is turned into [6][7]:

$$M_d\ddot{e} + B_d\dot{e} + K_d e = F_d \tag{6}$$

3.2. Double-weighting-factor Fuzzy Variable Impedance Control

For the reason that the manipulator's tool end contacts the environment in the process of force / position control, the environmental position and stiffness will change any time. The control method using fixed impedance parameters will achieve a good force tracking performance. However, error and mutation will cause the motion trail to be changed, which will probably result in the force tracking errors, and even overshooting and collision. Even worse, the manipulator's tool end and the environmental surface may be damaged. Hence, such method fails to satisfy the requirement of task. Finally, the constant force tracking controlled by variable impedance parameters is selected. A sacrifice of the error range for position control enables position to vary in the allowed error range, thus to achieve an intelligent force control of the target impedance.

Owing to the fact that the manipulator system is always in low-velocity movement, the impact of Md can be ignored. It is only necessary to make adjustment of Bd and Kd. To ensure a better control of position and force, the impedance parameters B_d and K_d are adjusted by fuzzy control in real time. In this way, force can be better tracked, overshooting reduced and stability improved, within the error range of position.

The process of fuzzy variable impedance control is shown in Figure 3. After the contact force F_e at the end of manipulator is measured, the grinding tool compensation should be done. The weight of the tool should be subtracted to make the contact force ${}^bF$ more accurate. After the contact force F_e is transformed from tool coordinate into manipulator coordinate, we get the result ${}^bF_e$. The difference between ${}^bF$ and the expected contact force is made as input 1 and sent to the fuzzy controller. Through the manipulator's inner-loop position control, the terminal position (speed) is subtracted from the expected position (speed), and the difference is made as input 2 and sent to the fuzzy controller. After the initial value of the target damping and of the target stiffness have been worked out, the damping and stiffness increment for the two fuzzy controllers are plugged into the impedance control. For the reason that the factors such as the measured contact force, the set expected force, environmental position and so on keep changing, the fuzzy controller produces damping and stiffness increment in real time. Hence, the system achieves the variable impedance control according to environment, and simulates human consciousness to have a control of force, thus to complete a task. The expected force F_d is set according to the task requirement.

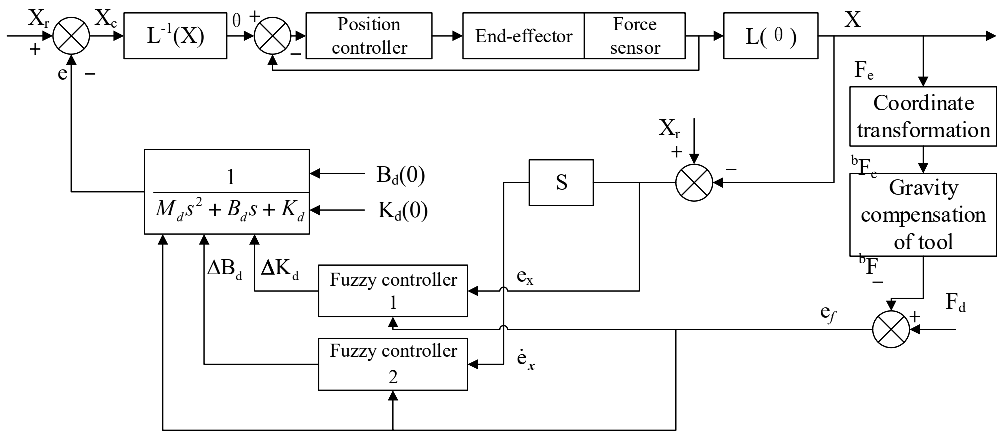

Figure 3. Double fuzzy variable impedance control system

Two fuzzy controllers are designed. The input into one fuzzy controller is the position error e_x and the force error e_f, while the input into the other fuzzy controller is the position error change ratio $\dot{e}_x$ and the force error e_f. The output from both fuzzy controllers is ΔK_d and ΔB_d. Finally, two fuzzy controllers with double input and single output are established to make adjustment of ΔK_d and ΔB_d respectively. Here the damping adjustment formula used to define damping control is shown as follows.

$$B_d(k+1) = B_d(k) + \Delta B_d(k) \tag{7}$$

The stiffness adjustment formula is:

$$K_d(k+1) = K_d(k) + \Delta K_d(k) \tag{8}$$

Plug ΔK_d and ΔB_d that are output from the fuzzy controller into (7) and (8) respectively, to have the target damping B_d and the target stiffness K_d of the impedance model adjusted.

The fuzzy control is also the class I non-linear controller. It simulates experts' priori knowledge to do reasoning and approximation. However, for the non-linear system with time-varying parameters, the control rule fails to be learned online and self-adjusted. Hence, the two fuzzy controllers are designed as the double-weighting-factor fuzzy controller, in order to improve their self-adjusting capability. Suppose the input fuzzy quantities are E_x, $\dot{e}_x$ and E_f, and the output fuzzy quantity is U.

Take the stiffness fuzzy controller 1 as an example. For a two-dimensional fuzzy controller, the fuzzy control rule can be approximately expressed with the following formula, when the domains of discourse of the input position error E_x, the force error E_f and the output U are classified according to the same level.

$$U \approx -\frac{E_x + E_f}{2} \tag{9}$$

In this formula, the control rule for the fuzzy controller stays unchanged, and cannot be adjusted. For different controlled objects, weighting factors are added to formula (9), to generate control rules with weighting factors, shown as follows.

$$U \approx -\left\{\alpha E_x + (1-\alpha)E_f\right\}, \alpha \in [0,1] \tag{10}$$

In formula (10), α is the weighting factor. By selecting different values for the weighting factor α, the degree of weighting done to U by E_f, and E_f can be changed, thus to have the control rule adjusted.

When the environmental equivalent stiffness k_e is high and the grinding tool at the end of manipulator contacts the environment, slight movement will result in a large contact force, when a high target impedance stiffness K_d should be chosen to have the manipulator sense a high environmental stiffness and make a slight movement under the action of the same contact force. Therefore, as the fuzzy controller e_f takes a greater proportion, its weighting should be increased, while the fuzzy controller e_x takes a smaller proportion, its weighting should be reduced. Conversely, when the environmental equivalent stiffness k_e is low and the grinding tool at the end of manipulator contacts the environment, slight movement will result in a large contact force, when a low target impedance stiffness Kd should be chosen to have the manipulator sense a low environmental stiffness and make a vigorous movement under the action of a small contact force. Therefore, as the fuzzy controller ex takes a greater proportion, its weighting should be increased, while the fuzzy controller ef takes a smaller proportion, its weighting should be reduced[8][9].

To sum up, for the reason that the requirements on deviant weight vary, different weighting factors are chosen to have the control rule self-adjusted. Here a fuzzy controller with double weighting factors is used. When the weight of e_f is high, the control rule is adjusted by α_1. When the weight of e_x is high, the control rule is adjusted by α_2. The analysis formula for control rule can be expressed as follows.

$$U = \begin{cases} -\left\{\alpha_1 E_x + (1-\alpha_1)E_f\right\}, & E_x = 0, \pm 1 \\ -\left\{\alpha_2 E_x + (1-\alpha_2)E_f\right\}, & E_x = \pm 2, \pm 3 \end{cases} \tag{11}$$

In this formula, $\alpha_1, \alpha_2 \in [0,1]$.

The designed double-weighting-factor fuzzy controller is shown in Figure 4.

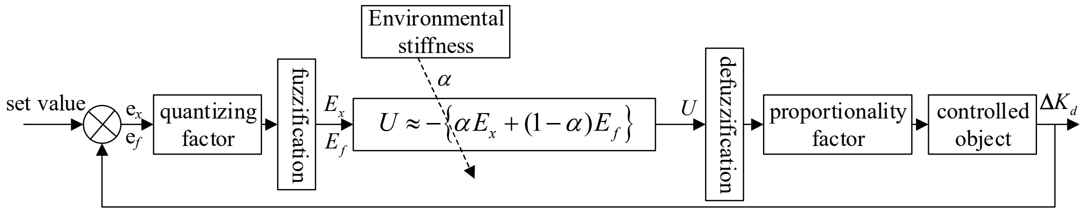

Figure 4. Double-weighting-factor Fuzzy Controller

Suppose α meets the following conditions.

$$\alpha = \begin{cases} \alpha_1 = 0.4 & K_e > 40N/mm \\ \alpha_2 = 0.6 & 0 \le K_e \le 40N/mm \end{cases} \tag{12}$$

After the quantifying factor and scaling factor normalize the position error and force error, the input quantity of fuzzy controller is converted. The ranges of the variation of e_x, $\dot{e}_x$ and e_f are $[-1\times10^{-4}, 1\times10^{-4}]$,[-0.1m/s,0.1m/s] and [-0.25N,0.25N] respectively. The domain of discourse is chosen as follows.

$$\{E_x\}=\{E_f\}=\{U\}=\{-3,-2,-1,0,1,2,3\}$$

The fuzzy output linguistic variable is divided into five fuzzy sets (NB, NS, ZE, PS and PB). In the domain of discourse, the Gaussian distribution function is chosen as the membership function. The fuzzy rule table is made as required, as shown in Table 1.

According to the fuzzy rule table, we, by defuzzification, can get the output value ΔK_d of the fuzzy controller. In the same way, we can get ΔB_d through fuzzy controller 2.

Table 1. Table for fuzzy control rules

ΔK_d		e_f				
		NB	NS	ZE	PS	PB
e_x	NB	NB	NS	ZE	PS	PS
	NS	NS	NS	ZE	ZE	PS
	ZE	NS	ZE	ZE	ZE	PS
	PS	NS	ZE	ZE	PS	PS
	PB	NS	NS	PS	PS	PB

4. Simulation

Simulation study is done to the double-weighting-factor fuzzy variable impedance control. Suppose that the manipulator is in linear motion, and the initial value of environmental stiffness is 5,000N/m, expected force 5N, and the initial value of manipulator force / position 0. The initial impedance parameters are set as M_d=1kg·m^2, B_d=300Ns/m and K_d=500N/m. Figure 5 shows how the contact force tracks the expected force under the condition that the environmental stiffness is fixed. It is found out that the force tracking tends to be stable when t is 0.9s. Figure 6 shows how the contact force tracks the expected force when the environmental stiffness sharply drops to 3,000 N/m from 5,000 N/m. It is found out that before the environmental stiffness changes, the contact force has gradually track the expected force stably. When t=1.5s, the environmental stiffness decreases abruptly, and the contact force decreases with it. When t=2.7s, the contact force begins to track the expected force stably.

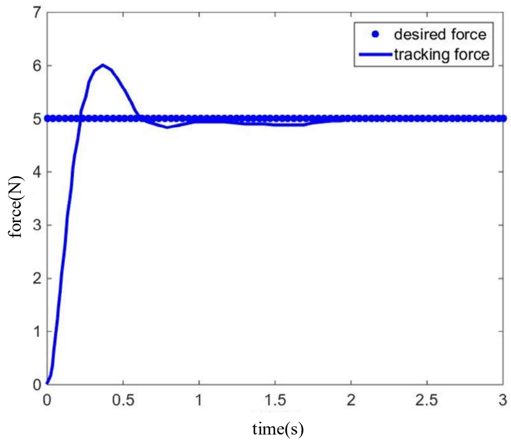

Figure 5. Force Tracking Curve (fixed environmental stiffness)

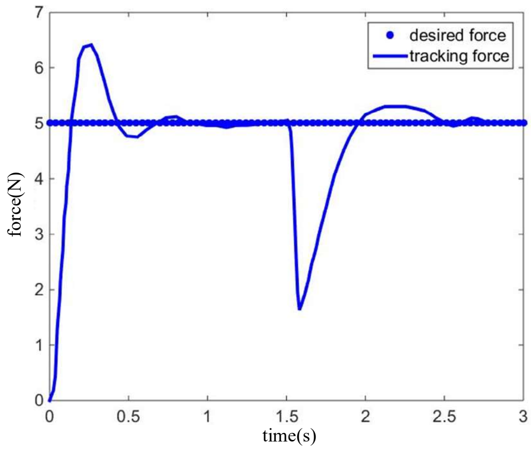

Figure 6. Force Tracking Curve (changeable environmental stiffness)

It can be seen from the simulation result that the proposed algorithm can achieve a good control of force and position, and can make rapid response when the environmental stiffness changes abruptly. It is able to sacrifice the positional accuracy for the re-tracking of expected force. To sum up, the proposed algorithm can better control the force and position, under the condition that the environmental parameters are time-varying.

5. Conclusion

(1) This work was financially supported by xxx fund. A three-degree-of-freedom dynamic model is established for the hydraulic series manipulator, under the condition that uncertainties and external interference are ignored. The model is calculated with MATLAB.

(2) According to the characteristics of the contact between manipulator end and the environment, and considering that time-variance of environmental parameters, a double-weighting-factor fuzzy variable impedance controller is designed to achieve a good control of force when the manipulator end contacts the environment.

(3) The simulation result suggests that the proposed control method achieves a good tracking control of both force and position.

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