TELKOMNIKA, Vol. 11, No. 9, September 2013, pp. 5200~5209
ISSN: 2302-4046

RBF Neural Network PID for Bilateral Servo Control System

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Abstract

Tele-operated bilateral hydraulic servo system with master-slave robot at the core can be complex manipulated in uncertain or extreme environment (such as space, seabed, radicalization, battlefield, etc.). In this paper, a novel force feedback bilateral servo system is presented, based on analysis of bilateral servo system at home and abroad, which adopts tuning PID control algorithm with RBF neural network at the same time. From the simulation results, the novel force feedback bilateral servo system is presented to verify the effectiveness of the proposed control algorithm. The control briefness, fast response, strong robustness, good disturbance rejection capability and good adaptive capability can be obtained. It is also revealed from simulation results that the proposed control algorithm is valid for force feedback bilateral servo system and also provides the theoretical and experimental basis.

Keywords: *force feedback, bilateral servo control system, RBF tuning PID, control algorithm*

1. Introduction

Since the first Master-Slave tele-operation manipulator was created in the 1940s [1]. After decades of development, the master slave tele-control robot [2] with the force tele-presence has been widely used in some dangerous environment which has high temperature, high pressure, strong radiation and suffocation, such as the development of space, underground and underwater, atomic reactor maintenance operations, fire, flood, earthquake and so on. Master-Slave manipulator was an assistance for human. Many countries have began to study the master-slave manipulator, such as the United States, Russia, Germany, Japan and other countries, and achieved good application effect. Its important of in technical field was revealed [3].

The bilateral servo control is a key technology in tele-operation control, which can provide the force sence in the operation process for operators, and enhance the operating performance and speed. Experiments show that the operating performance of tele-operation control with force feedback is doubled to tele-operation control without force feedback [4]. The bilateral servo control tele-operation technology is one of the effective methods to realize the force sense and visual tele-presence [5].

In this paper, PID control strategy is applied to improve its performance in the two-way force servo on the basis of two-way force servo tele-operation technology,taking into account the parameter characteristics of two-way force servo system are likely to change in actual working conditions, the traditional PID parameter tuning method already can not satisfy the real-time, accurate control conditions. The PID algorithm was done various improvements. Emerging selective control PID-PD, control PID control and adaptive PID control algorithm [6], especially in recent years with the research of the intelligent control and development of the so-called intelligent PID controller was formed from combining intelligent control and conventional PID control, the controller has caused widespread concern and great interest and has been successfully applied [7], scholars has researched some intelligent PID algorithm and controllers,

Received February 27, 2013; Revised June 7, 2013; Accepted June 19, 2013

such as parameter fuzzy PID controller [8, 9], PID controller based on genetic algorithm [10, 11], neural network PID controller [12, 13], PSO-PID controller [14], Immune PID [15] and so forth, and achieved good control effect.

Radial basis function neural network is a forward neural networks with good performance, it has a good ability of generalization and Small amount of calculation, its learning speed is also much faster than the other algorithms, so it has been widely used in system identification and parameter estimation [16].

In this paper, a novel force feedback bilateral servo system is presented, based on analysis of bilateral servo system at home and abroad, which adopts tuning PID control algorithm with RBF neural network.It uses a selftuning method of PID control parameters based on RBF neural network, combining theneural network with PID, on the basis of conventional PID performance, using the adaptive capacity of neural network to fine-tune the control parameters of the system, so that a stable PID controller with self-tuning capability was Construct to adapt the changes of work parameters of the bilateral force servo control, to get better control effects. Scene experiments show that the proposed method can achieve better tracking results.

2. New Type Servo System Mathematical Model

2.1. Brief Introduction to the Bilateral Servo Control System

At present, the commonly used control systems are force feedback directly type (Figure 1), Parallel Control Strategy Diagram (Figure 2), symmetrical position type (Figure 3), deviation of force feedback type (Figure 4) and so on. A variety of master-slave servo control method, each have advantages and disadvantages of four double servo control systems, as shown in Table 1, compared with four kinds of control system, the most commonly used and the most effective one is the force-location type, however, this control strategy exists spring effect, which makes the operator have the feeling of manipulation of heavy even when no-load operation [17-19]. Therefore, it needs a new way to solve the problem.

Table 1. Contrast Analysis of Four Bilateral Control Systems

Types of control	Sensor	Advantages	Disadvantages
Force feedback directly type	Torque sensor	Simple implement	More influence by main hand and large influence when fetching the higher stiffness object
Deviation of force feedback type	Torque sensor	Less influence by main hand	Large influence when fetching the higher stiffness object
Symmetrical position type	Displacement sensor	Simple implement,Realize the force feedback on displacement difference	Affected by the system time delay
bilateral type	Force and displacement sensors	Ease the feedback force impact on the joystick	Obviously, the Following features of Follower institutions influence on joystick goes weak

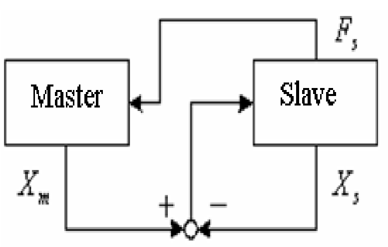

Figure 1. Diagram of Force Feedback Directly Type

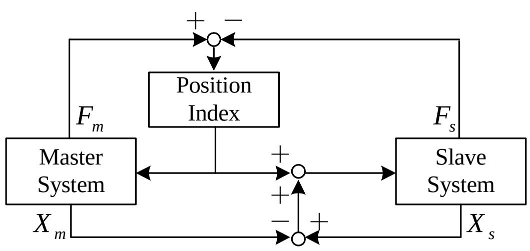

Figure 2. Improved Parallel Control Strategy Diagram

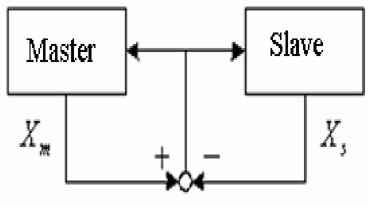

Figure 3. Diagram of Symmetrical Position Type

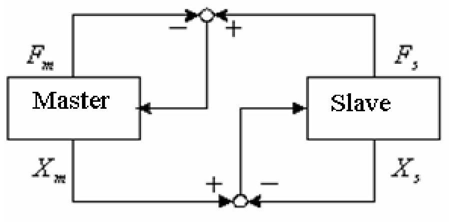

Figure 4. Deviation of Force Feedback Type

2.2. A Novel Bilateral Servo Control System

The principle of the improved parallel force bilateral hydraulic servo control system is shown as Figure 5. The control strategy that the slave mechanism always follows the manipulator has been used internationally, but it is not very idea for the force telepresence from the control effect. The improved parallel control strategy presented by this paper combines the advantages of force error and parallel bilateral servo control, uses the error between the operating force of the manipulator and the working resistance of the slave mechanism as the control signal to control the master's motion. The feedback force is related to the force error between the master and the slave, the slave driving force is related to the difference force between the master and the slave and the displacement difference between the master and the slave. So it improves the problems exist in the existing control method that the impact force is too large when the slave contacts the object with big rigidity, and that the master-slave position following characteristics is bad.

3. Description of System

3.1. Structure of Construction Robot

The construction robot is based on the boom of the excavator, the bucket is replaced by an single degree of freedom end-effector to form an four-DOF series joint type manipulator, as shown Figure 5. The end-effector opens and closes to grasp the object by a pair of mesh gear, and there are in sections on the tooth surface to enhance the reliability of grasping the object. In order to bear greater working load, the arm of the construction robot are driving by hydraulic power, four cylinders are used to control the four-DOF of the robot. The hydraulic system are composed of hydraulic station, oil circuit, electronic-hydraulic controlled proportional reversing valves and their controllers and cylinders. The proportional reversing valves and their controllers are the core of the electro-hydraulic control subsystem, which realize the flow control of the cylinders, namely speed control and reversing control.

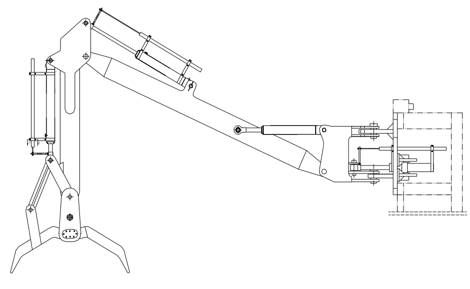

Figure 5. 4 DOF Engineering Robot Structure Chart

3.2. Tele-operation Robot System

In a tele-operated manipulation system, the operator needs not only a visual representation but also a force representation of a system existing in a remote place. Those devices of sense of force, at present, have problems, such as insufficiencies in the display functions and complications in their constitutions.

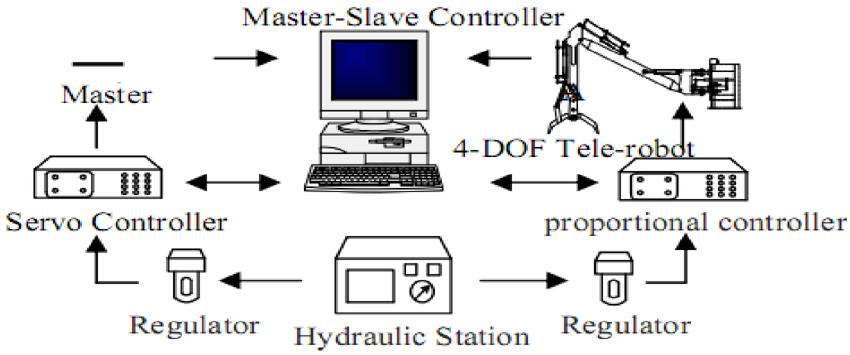

Figure 6. Master-slave System for Remote Control

A conceptual illustration of a tele-operated manipulation system for this study is given in Figure 6. The figure shows that the system is constructed as a master-slave system and that both manipulators for the master and the slave consist of 4-DOF type actuators. Moreover, it is illustrated that a machine tool for grinding is implemented at the end-effecter of the slave manipulator. In a tele-operated master-slave system as shown in Figure5, the master has to play two roles, firstly as a reference input device to the slave, and secondly as a sense of force device. Here, the term “sense of force” means a function that allows the operator to feel a force that is fed back to him from the slave [20-22].

4. Control Algorithm

4.1. Radial Basis Neural Network Setting PID Control Strategy

The Radial Basis Function(RBF) is a neural network which was put forward by J.Moody and C.Darken in the late 1980s, it is a three layer feed forward network with single hidden layer, is a kind of local approximation of the neural network. The network’s characteristic is that to enter a local area of the space only a handful of connection weight affect the output of the network, so that the local approximation network has the advantage of fast learning. RBF learning methods include k-means method, the OLS (Orthogonal Least Squares) and gradient descent method, etc.

In the process of practical application, the object features and models are changing frequently, just changing slowly. Setting and well optimized PID parameters may no longer have a very good control effect after a period of time. In order to make the production process always keep a good control effect, the parameters of PID controller need to be adjusted and optimized online. To meet this requirement, a neural network intelligence PID controller has the characteristics arises at the historic moment. The neural network intelligence PID controller can identify the model and features of the controlled object through identifier; and on the basis of identification, it can realize PID parameters online adjustment and optimization through the neural network controller.

4.2. The PID Control based on RBF Neural Network [23-25]

There are many function form of RBF neural network, Gauss function was selected in this article as the hidden layer node function according to its unique advantages :
Gauss function :

$$f(x) = \exp\left(-\frac{\|x-c\|^2}{2b^2} \right) \qquad (1)$$

The structure of RBF neural network was showed as below.

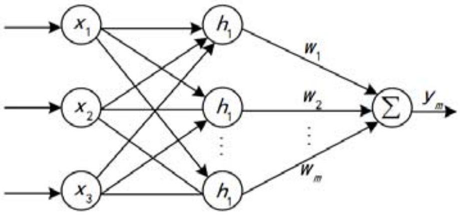

Figure 7. The Structure of RBF Neural Network

In the structure of RBF neural network, r(k) is input of network, h=[h1,h2,…,hm]T is the radial basis vectors of network, hj is the Gauss function,which showed as formula 1:

$$h_j = \exp\left(- \frac{\left\| r\left(k - C_j\right) \right\|^2}{2b_j^2} \right) \quad (2)$$

Where j means 1,…,m, Bj is the base width parameters based on node j, bj is greater than zero, Cj is the the center vector of j-th node of the network, Cj means [c11,…,c1m]T, B means [b1,…,bm]T.

The weight vector of network as follows:

$$W = [w_1, \cdots, w_m]^T \quad (3)$$

The network input of RBF was showed in formula 3:

$$u_n(k) = h_1 w_1 + \cdots + h_j w_j + \cdots + h_m w_m$$
(4)

Where m is the counts of hidden layer neurons of RBF neural network. The law of control was shows as below：

$$u(k) = u_p(k) + u_n(k) \quad (5)$$

The performance indicator of Neural network adjustment was showed in formula 5:

$$E(k) = \frac{1}{2}\left(u_n(k) - u(k)\right)^2 \quad (6)$$

In the current applications of RBF neural network, some parameters should be determined, such as the counts of hidden layer neurons, a m center vector of RBF, the width of the base function b and each connection weight w from hidden layer to output layer.

In this article, d is selected as the center distance. Base width is $b = d / \sqrt{2L}$. The weight of output unit is calculated by the gradient descent. The iteration algorithm of output weight w, node center c and node base width b for the RBF neural network is given as follows:

$$w_j(k) = w_j(k-1) + \eta\left(y(k) - y_m(k)\right)h_j + \alpha\left(w_j(k-1) - w_j(k-2)\right) \quad (7)$$

$$\Delta c_{ji} = (y(k) - y_m(k))w_j \frac{x_j - c_{ji}}{b_j^2} \quad (8)$$

$$b_j(k) = b_j(k-1) + \eta\Delta b_j + \alpha(b_j(k-1) - b_j(k-2)) \quad (9)$$

$$c_{ji}(k) = c_{ji}(k-1) + \eta\Delta c_{ji} + \alpha(c_{ji}(k-1) - c_{ji}(k-2)) \quad (10)$$

$$\Delta b_j = (y(k) - y_m(k))w_j h_j \frac{\|X - C_j\|^2}{b_j^3} \quad (11)$$

Where η is the learning rate, α is momentum factor.

Because the gradient descent method is easy to fall into local optimal value, slow convergence speed, aiming at this problem, this paper adopts an improved algorithm, which is the variable step size gradient descent method. So an appropriate learning rate is a main factor affecting the control results. In order to avoid the instability of network initial training value, make the training weights jump out the local optimum, this paper presents a variable step gradient descent method.

$$\eta(k+1) = \eta(k) - \beta\frac{\Delta e(k)}{e(k)} \quad (12)$$

$$\Delta e(k) = e(k) - e(k-1) \quad (13)$$

4.3. Parmaments of Controller based on the BRF Tuning PID

The PID control system (Figure8) based on RBF network can be obtained by incremental PID controller.

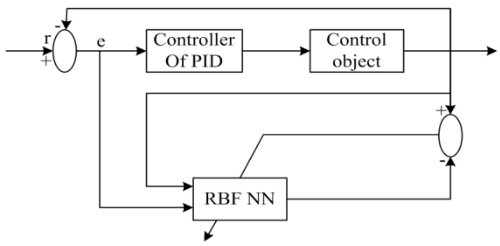

Figure 8. PID Control System based on RBF Network

The control error is given as following：

$$e(k) = r(k) - y(k) \quad (14)$$

The three inputs of PID is given following as ：

$$xc(1) = e(k) - e(k-1) \quad (15)$$

$$xc(2) = e(k) \quad (16)$$

$$xc(3) = e(k) - 2e(k-1) + e(k-2) \quad (17)$$

Control algorithm is given as:

$$u(k) = u(k) + k_p(e(k) - e(k-1)) + k_i e(k) + k_d(e(k) - 2e(k-1) + e(k-2)) \tag{18}$$

The tuning index of neural network is selected as:

$$E(k) = \frac{1}{2}e^2(k) \tag{19}$$

The gradient descent method is used for adjustment of k_p, k_i, k_d :

$$\Delta k_p = -\eta\frac{\partial E}{\partial k_p} = -\eta\frac{\partial E}{\partial y}\frac{\partial y}{\partial u}\frac{\partial u}{\partial k_p} = \eta e(k)\frac{\partial y}{\partial u}xc \tag{20}$$

$$\Delta k_i = -\eta\frac{\partial E}{\partial k_i} = -\eta\frac{\partial E}{\partial y}\frac{\partial y}{\partial u}\frac{\partial u}{\partial k_i} = \eta e(k)\frac{\partial y}{\partial u}xc \tag{21}$$

$$\Delta k_d = -\eta\frac{\partial E}{\partial k_d} = -\eta\frac{\partial E}{\partial y}\frac{\partial y}{\partial u}\frac{\partial u}{\partial k_d} = \eta e(k)\frac{\partial y}{\partial u}xc \tag{22}$$

Where, $\frac{\partial y}{\partial u}$ can be obtained by the identification of neural network. The $\frac{\partial y(k)}{\partial u(k)}$ is almost equal to $\frac{\partial y_m(k)}{\partial u(k)}$, and x_1 is a one dimensional vector of the u, then $\frac{\partial x_1}{\partial u} = 1$.

$$\frac{\partial y(k)}{\partial u(k)} \approx \frac{\partial y_m(k)}{\partial u(k)} = \frac{\partial\sum_{j=1}^{m} w_j h_j}{\partial u(k)} = \frac{\sum_{j=1}^{m} w_j \partial \exp\left(-\frac{\|x_1 - c_j\|^2}{2b_j^2}\right)}{\partial u(k)}$$
$$= \frac{\sum_{j=1}^{m} w_j h_j \frac{c_j - x_1}{2b_j^2}\partial x_1}{\partial u(k)} = \sum_{j=1}^{m} w_j h_j \frac{c_j - x_1}{2b_j^2} \tag{23}$$

So we can obtain：

$$\frac{\partial y(k)}{\partial u(k)} = \frac{\partial y_m(k)}{\partial u(k)} = \sum_{j=1}^{m} w_j h_j \frac{c_j - x_1}{2b_j^2} \tag{24}$$

5. System Simulation and Analysis Comparison

The bulk modulus of liquid is selected as 700MPa. Liquid density is selected as 855kg/m3. Piston diameter of Hydraulic cylinder is selected as 0.035m. Piston diameter of Hydraulic cylinder is selected as 0.063m. Flow coefficient of the valve port is selected as 0.43. Load viscous damping coefficient is selected as 8KN/(m/s), Amplifier gain is selected as 150mA/V. Coefficient of proportional valve is selected as 3X10-6m/mA. The natural frequency of the hydraulic cylinder is selected as 42.6rad/s. Relative damping coefficient is selected as 0.705. There can be derived the open-loop transfer function of system according to the parameters above:

$$G(s)=\frac{Y(s)}{U(s)}=\frac{51894}{s(s^2+74.4s+34596)} \quad (25)$$

In the RBF tuning of PID control, the three parameters of PID control were given as follows: Kp is 30, Ki is zero, Kd is 0.13. Take the Sampling time as 1ms, network weights learning parameter η as 0.5 and α as 0.08. The network structure is 3-4-1, take random numbers between zero and one as the Network initial weights w, take parameter values of the Gaussian function C as [-3 -1 1 3]T and B as [0.5 0.5 0.5 0.5]T.

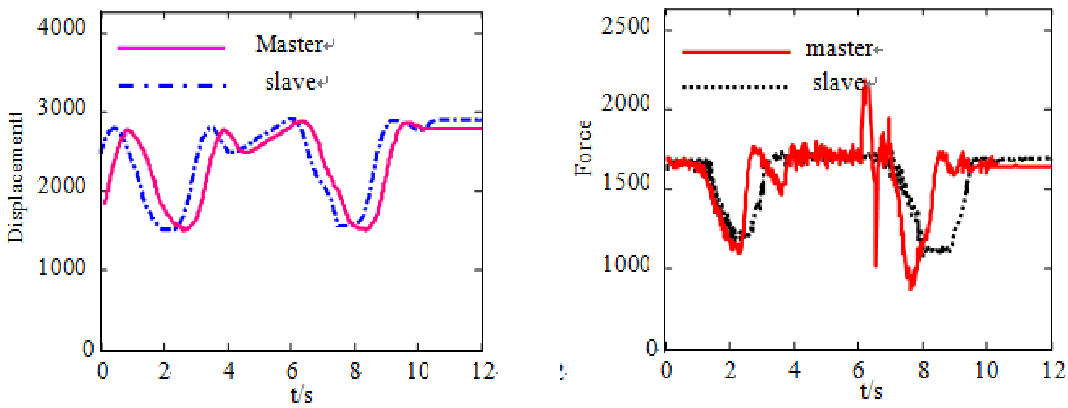

Figure 9. The Displacement and Force Curve of Force Feedback Directly Type (PD)

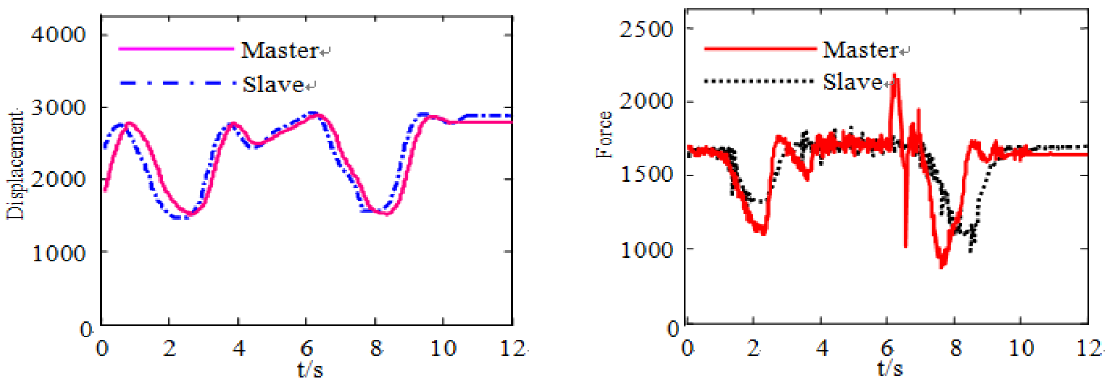

Figure 10. The Displacement and Force Curve of Improved Parallel Control Strategy Diagram (PD)

The simulation results show in figure 9-10. A result of using PID control method is shown in Figure 9, results of the RBF tuning PID control strategy is shown in Figure 11.

From in the Figure 9, there exists the position error when the master hand with force feedback bilateral servo control strategy follows the slave hand, which the main hand lags from hand. Force feedback signal has local shock relative to operator manipulates, affects the stability of the system.

It can be seen from Figure 10, with the improved parallel bidirectional control strategy, due to the salve controlling signal was controlled by the deviation of the position and the force existed between master and slave force, it makes the slave follow the master 's movements synchronously, the system response speed was greatly improved.

From the Figure 11, the active manipulator is better than the slave manipulator overall at displacement of the following features. The active manipulator can follow the slave manipulator well. But for the reason of RBF neural network with learning time delay itself and uncertainty of control system, system is not stable or shock at part. Local displacement oscillation phenomena can be found out clearly in the process of location to follow from this figure.

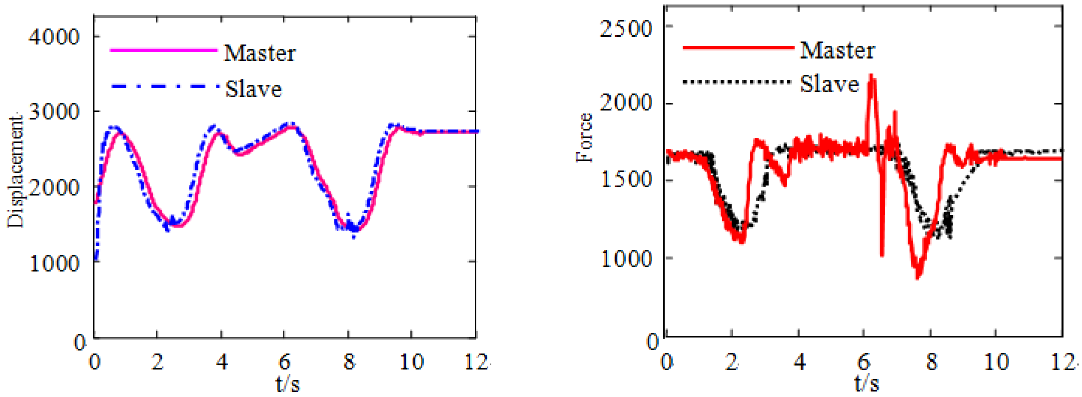

Figure 11. The Displacement Curve and Force Curve of RBF Tuning PID

6. Conclusion

Through analyzing the previous side-by-side type bilateral servo control strategy, then we propose the RBF tuning PID control strategy, which can make the BRF neural network optimize by the three parameters of PID, and achieve the aim about dynamic performance of initiative hand with follower hand. Results of the simulation indicate that the control means and the control principles raised by testing system can achieve the aim of following features. In addition, the arithmetic is simple and reliable, fast constriction, Good real-time, strong robustness and fast response. In the meantime, it offers the basis of theory and experiment about father studying side-by-side type bi-directional servo control strategy.

Acknowledgments

The authors wish to thank the helpful comments and suggestions from my colleagues. This work is supported by the study fund of Sichuan province science and technology support projects at Chengdu (No.2011GZX0065).

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