Research on Control Method for Time Delay of Internet-Based Tele-Operation Manipulators

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Abstract

In this paper, a parameters self-learning PID controller algorithm based on modified BP neural network is proposed to eliminate the influence of time delay on the stability and maneuverability of tele-operation manipulators. This control algorithm adjusts the three parameters of PID controller on line through BP neural network. Conjugate gradient method is used for real-time adjustment of weighted coefficient of BP neural network so as to adjust the output parameter of PID controller. The model of three-joint manipulator with three degrees of freedom (3-DOF) was established. The simulation results show that force tracking performance of master and slave manipulators is good, the maximum error is 0.15. The position tracking performance of slave manipulator is stable, the amplitude decay can be ignored, the maximum error is 3.9 and time delay is 0.3s. This control algorithm has fine self-learning capability and robustness. It had better time delay control effect and could improve the operability of internet-based tele-operation manipulators.

Keywords: *Internet-based tele-operation, Time delay, Manipulator, Neural network PID control*

1. Introduction

Emerge of tele-operation manipulators makes human can fulfill complex tasks in harmful or inaccessible environment and create more social value [1-3]. Tele-operation manipulators can word in the dangerous environment, for example, deep-sea detecting, rescue after major natural disasters. And this expands the home range of human greatly.

With the rapid development of computer network technology, it is applied to internet-based tele-operation manipulator system and tele-operation technology is promoted to a new level. The existence, randomness, data packet loss and disorder severely influence the stability and maneuverability of system. So, the analysis and study of time delay of tele-operation manipulator system has a very important significance.

Park *et al.*, [4] apply sliding mode control approach to tele-operation manipulators system and compensate the change of the time delay by use of the robustness of sliding mode to parameters. Sliding mode controller is used for master manipulator and impedance controller is used for slave manipulator. Conventional sliding mode controller is corrected, nonlinear gain is added and the operating performance of system with varying time delay is compensated. This control method can ensure the stability of tele-operation system and it is also can be proved that there is no relationship between this stability and time delay. That is, for tele-operation system with varying time delay, we can ensure the stability only if the size of time delay is known. Sano *et al.*, [5] apply a control method based on H_∞ theory to tele-operation system, time delay is regarded as disturbance and design controller to make system has robustness to varying time delay. System disturbance is disposed by impedance normalization of master manipulator and the controller realized by gain scheduling. In order to gain favorable system performance, the H_∞ controller can be also designed by gain scheduling when time delay change quickly. The using of H_∞ control theory can get anticipant stable control, decrease the influence of time delay on system, and meet the requirement of system performance, make system have robustness to external disturbances. By means of Lyapunov stability theorem, Jankovi *et al.*, [6] used Lyapunov-Krasovski and Lyapunov-Razumikhin functions to realize the stable control when system is related to time delay or not. This method can be applied to internet-based tele-operation manipulators system. For systems with randomly varying time delay, its stability algebra criteria can be obtained by use of Razu-mikhin-type theorem. Its advantage consists in being able to realize the control effect consideration to stability and operability. But the defect is also obvious. Firstly, the conservatism of Lyapunov-like function method is larger than frequency domain analysis method. Secondly, this kind of methods calls for some requirements in time delay. That is to say, time delay must be bounded and even the criterion gained by use of this kind of method is just sufficient condition when knowing the change rate of time delay. Zhang *et al.*, [7] pointed that LQG optimal controller can be designed for tele-operation manipulators system when the transmission delay characteristics of system satisfy certain conditions. If the transmission delay of system is random, the internet-based tele-operation manipulators system can be controlled as a system with time delay by combining Lyapunov-like and Backstepping technology. But this method requires enough understanding to time delay characteristics of system and it has some limitations. Wang *et al.*, [8] proposed a prediction method based on artificial neural network to decrease the influence of time delay on tele-operation system. Prediction model applies reverse transmission neural network and the weights of network are renewed by back-propagation algorithm. It can be known that this prediction method has certain feasibility from the 3D graphics motion simulation in the virtual scene. Lawrence *et al.*, [9] proposed a position and force feedback four-channel structure, the force and speed were transferred between master and slave manipulators. Because adopting four-channel transmission can get the environment impedance information more accurately, four-channel control method is much effective in realizing transparency. Hashtrudi-Zaad *et al.*, [10] obtained transparency and stability of four-channel system by selecting feedback control parameters and force feedback compensation parameters. At the same time, two kinds of three-channel control structures were given and they were proved to have good results. Although four-channel control method has big superiority in analyzing the transparency of tele-operation system, but it requires feed back all environmental information of slave manipulator. This will make control structure complex, lead to can not discuss the stability intuitively and more complex control due to many channels striding time delay. Ferrel *et al.*, [11] proposed a supervisory control structure for path planning and collision avoidance experiment of remote robot. Its basic idea is that control circuit of master and slave manipulators are separated, operator is placed out of closed loop control which can decrease the influence of transmission delay on system. Supervisory control is a kind of most mature methods adopted earlier. A disadvantage of this method is that it can not provide telepresence. But with the development of artificial intelligence technology, the autonomous decision ability of robot system is strengthening continuously and the effect of human in supervisory control tends to be weaker and weaker.

A kind of modified BP neural network parameters self-learning PID control algorithm is proposed in this paper. The three parameters of PID controller are adjusted online by modified BP neural network and the object is controlled through closed loop. The weight adjusting algorithm of BP neural network adopts conjugate gradient method. SimMechanics model of 3-DOF manipulator is established and the proposed control method is researched on the time delay simulation platform based on TrueTime software.

2. Bilateral Servo Control Architecture with Force Deviation Feedback

In this paper, bilateral servo control architecture with force deviation feedback is adopted as the control structure of tele-operation manipulators system which is shown in Figure 1.

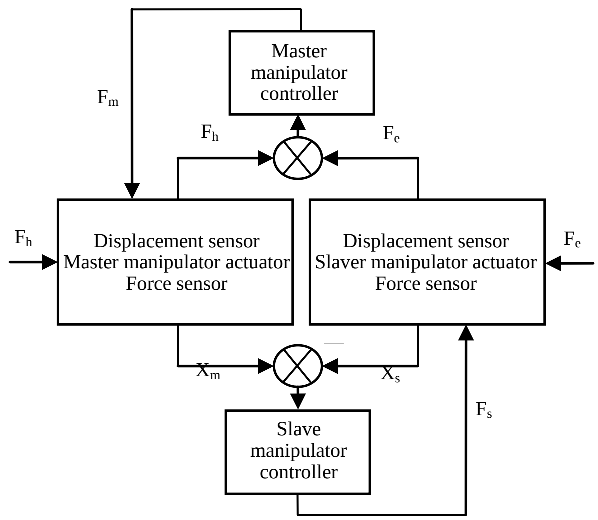


Figure 1. Bilateral Servo Control Architecture with Force Deviation Feedback

F_h is a force that the operator applies on the master manipulator, F_m is a reverse driving force that obtained by the master manipulator, F_s is driving force of slave manipulator, F_e is a force that the environment applies on the slave manipulator, X_m and X_s are the position of master and slave manipulators.

In order to realize that master manipulator can track the position of slave manipulator, the position error signal of master and slave manipulators is used to drive the slave manipulator. In order to provide the force telepresence for the operator, the force deviation signal of master-slave manipulators is used to drive the motion of master manipulator. The difference between the desired position of master manipulator and the actual position is used to simulate the force from human hands. In order to accurately control the position of the master manipulator, the force of the slave manipulator is introduced as the negative feedback and a closed loop control is formed. Master manipulator's actual position is namely the desired position of the slave manipulator. The position's error between the position of master manipulator and slave manipulator is input into controller, after calculating by the control algorithm, the desired slave manipulator control force is obtained. Then a closed-loop control is formed, so as to control the movement of the slave manipulator.

3. SimMechanics Model of 3-DOF Manipulator

After the analysis of tele-operation manipulators, we build a model of 3-DOF manipulator by use of SimMechanics software. Every module of connecting mechanism is shown in Figure 2. There have three revolute modules, three body modules, a machine environment module and a ground module. Revolute1, Revolute2 and Revolute3 represent the three revolute joints of manipulator. Body1, Body2 and Body3 represent pole1, pole2 and pole3 of manipulator. Joint Actuator1, Joint Actuator2 and Joint Actuator 3 are used to drive Revolute1, Revolute2 and Revolute3. Joint Sensor1, Joint Sensor2 and Joint Sensor3 are used to measure the angles of joints. Body Sensor is used to measure the trajectory of manipulator's end. Parameters of each module are set as follows.

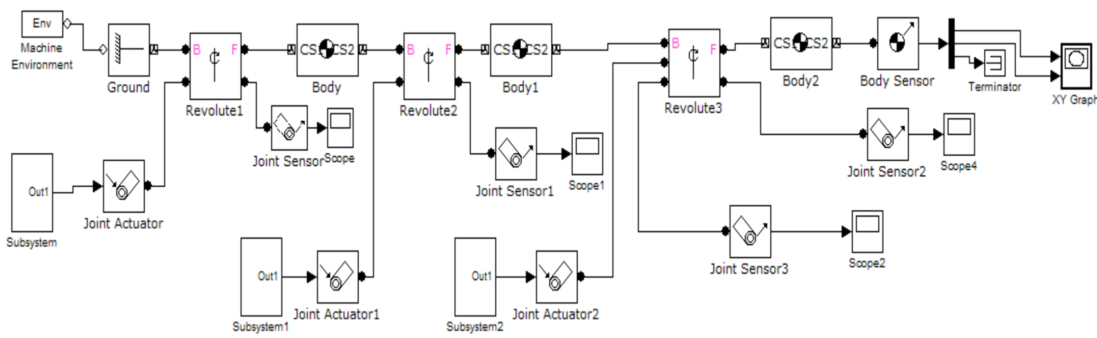


Figure 2. The Model of 3-DOF Manipulator by Use of SimMechanics Software

3.1. Set the Parameters of Environmental Module

The function of environmental module is to simulate the external gravity environment of manipulator. Settings window is shown in Figure 3.

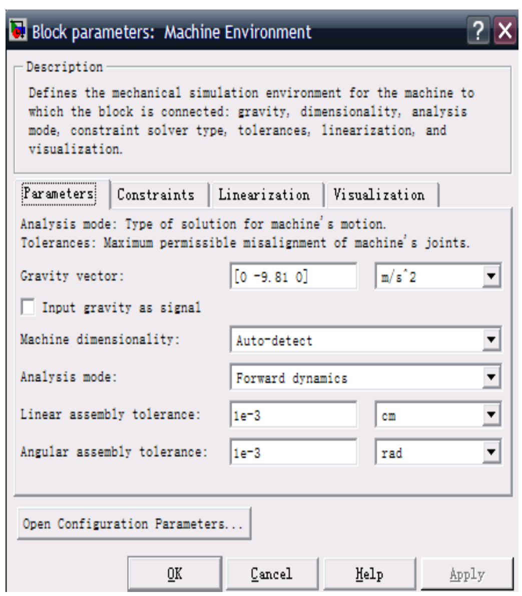


Figure 3. Setting Parameters of Environmental Module

3.2. Set the Parameters of Revolute Module

The main function of revolute module is to hinge so that the link mechanism is connected and rotated, the three degree of freedom manipulator require that Body1 rotates around vertical z axis, and Body2 and Body2 rotate around horizontal x and y axis. Settings window is shown in Figure 4.

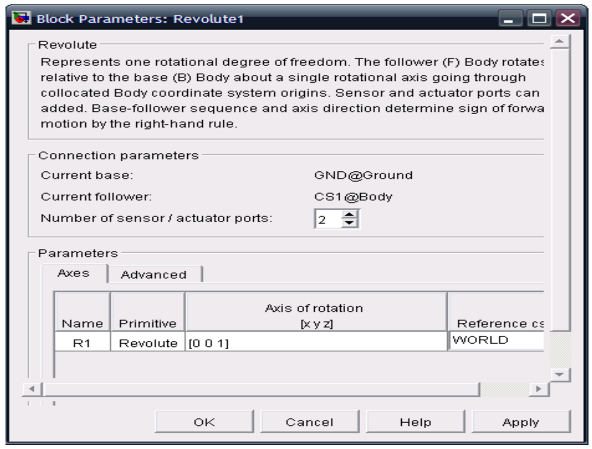
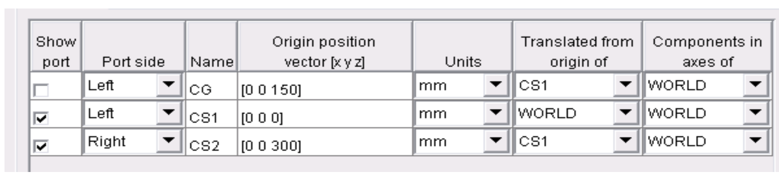


Figure 4. Setting Parameters of Revolute Module

3.3. Set the Parameters of Three Body Modules

Firstly, it is need to set a benchmark. Left is adopted as benchmark. Its coordinate is (0, 0, 0) and name it as CS1. Secondly, the coordinate of Right is set as (0, 0, 300) and name it as CS2. Hence, the length of the body1 is 300mm. Furthermore, the centre's coordinate of the body1 is (0, 0, 150) and name it as CG. Setting window is shown in Figure 5. The setting method of the other two body module's parameter is the same as the above method.



Show port	Port side	Name	Origin position vector [x y z]	Units	Translated from origin of	Components in axes of
☐	Left	CG	[0 0 150]	mm	CS1	WORLD
☑	Left	CS1	[0 0 0]	mm	WORLD	WORLD
☑	Right	CS2	[0 0 300]	mm	CS1	WORLD

Figure 5. Setting Parameters of Body Module

3.4. Set the Parameters of Joint Actuator Modules

Firstly, we select "Motion" option, afterwards select deg, deg/s and deg/s^2 in the "Angle" option, "Angular velocity" option and "Angular acceleration". Settings window is shown in Figure 6.

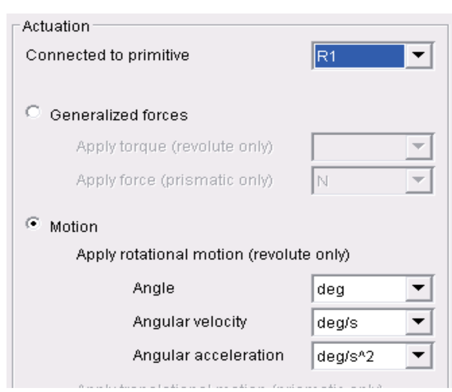


Figure 6. Setting Parameters of Joint Actuator Module

3.5. Set the Parameters of Joint Sensor Modules

We select "Angle" option. Settings window is shown in Figure 7.

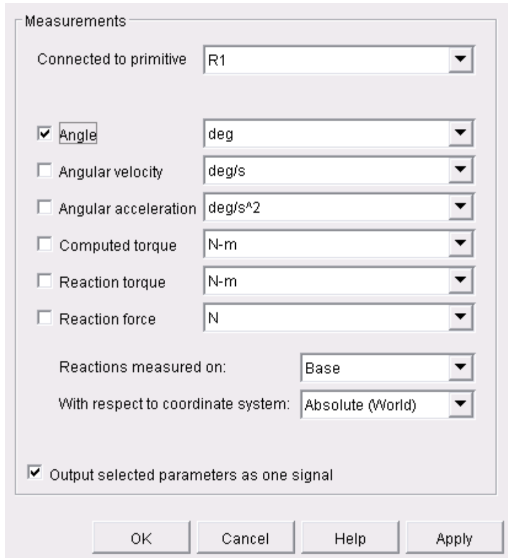


Figure 7. Setting Parameters of Joint Sensor Module

3.6. Set the Parameters of XYGraph Modules

The main function of XYGraph module is to display X-Y graph of signal by use of Matlab graphics window. Settings window is shown in Figure 8.

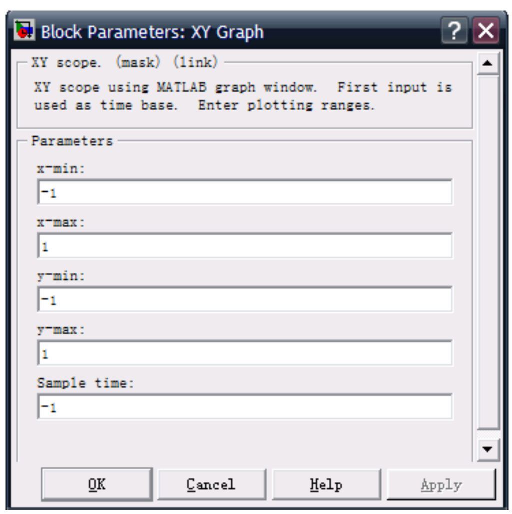


Figure 8. Setting Parameters of XYGraph Module

3.7. Run the Model and Visualization

In order to observe the movement of 3-DOF manipulator in the workspace and measure the trajectory curve of 3-DOF manipulator, the following options need to be set. We select "environment/Visualization" option in the "Simulation/Mechanical" of "Simulink" menu. The workspace of 3-DOF manipulator at some point is shown in Figure 9.

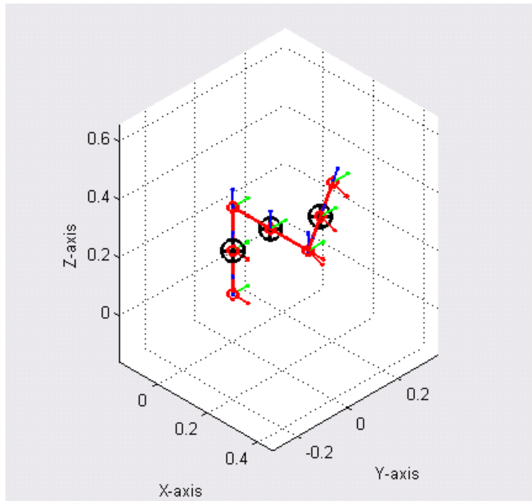


Figure 9. The Running Diagram of Model at Some Point

4. Setup the Time Delay Simulation Platform Based On TrueTime Software

Based on the control structure and principle of bilateral servo control architecture with force deviation feedback, we introduce the network control into the bilateral servo control system and design the time delay simulation platform based on TrueTime and Matlab/Simulink software. The Simulation diagram is shown in Figure 10.

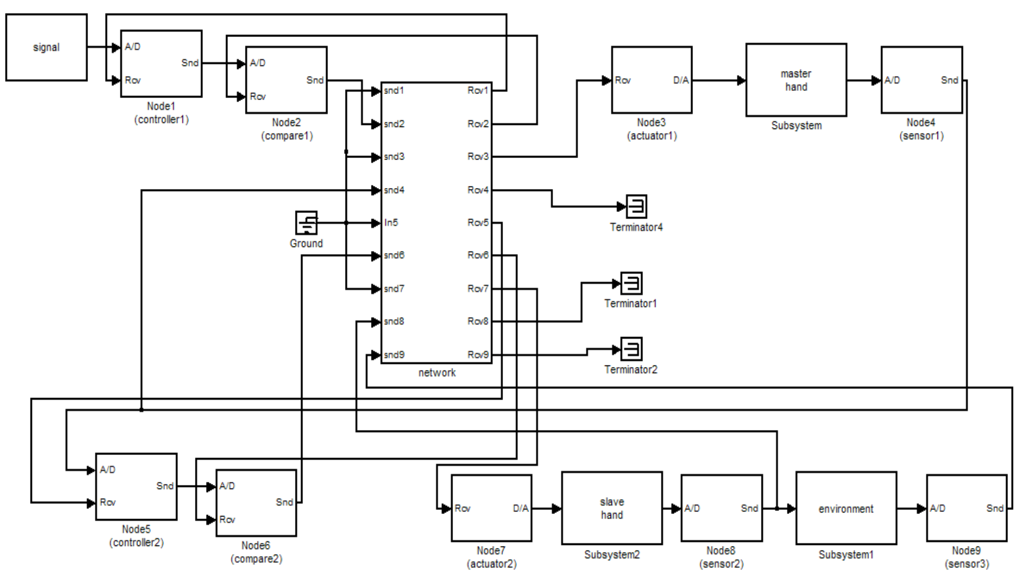


Figure 10. Simulation Diagram of Internet-based Tele-operation Manipulator System based on TrueTime

Among them, comparator nodes of each sensor, controller and actuator are implemented by TrueTime Kernel module. Network module is implemented by TrueTime Network module. The specific parameter setting is shown in Figure 11. Subsystem1 is environment model of system and its mathematical description is

$$F_e = K_{p_s}(x_s - x_{obstacel}) + K_{d_s}\dot{x}_s \qquad (1)$$

Equation (1) expresses the relation of action force F_e and the position x_s of slave manipulator. K_{p_s} and K_{d_s} are environmental parameters, $x_{obstacel}$ is the position of obstacle. When $K_{p_s} = K_{d_s} = 0$, this means that the manipulate dose not contact the environment and there is no external force on manipulator. When the slave manipulator contacts the environment, K_{p_s} and K_{d_s} will enlarge.

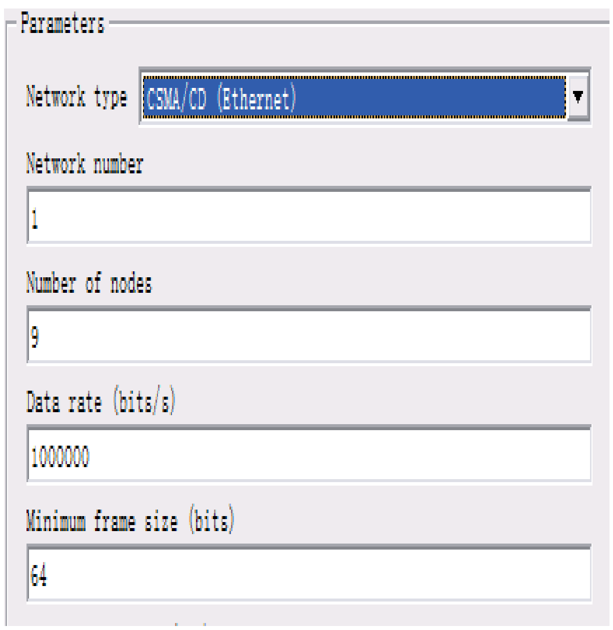


Figure 11. The Setting Dialog of TrueTime Network Parameters

5. The Design of Controller

5.1. The Structure of BP Neural Network

The structure of BP neural network which is adopted by this algorithm is shown in Figure 12. The layer's number of BP neural network is 3 and the numbers of neurons are respectively 4, 5 and 3. j is input layer, i is hidden layer and l is output layer. $w_{ij}^{(1)}$ is the weights between input layer and hidden layer. $w_{li}^{(2)}$ is the weights between hidden layer and output layer. In this network, the activation function of each hidden layer node is Sigmoid function.

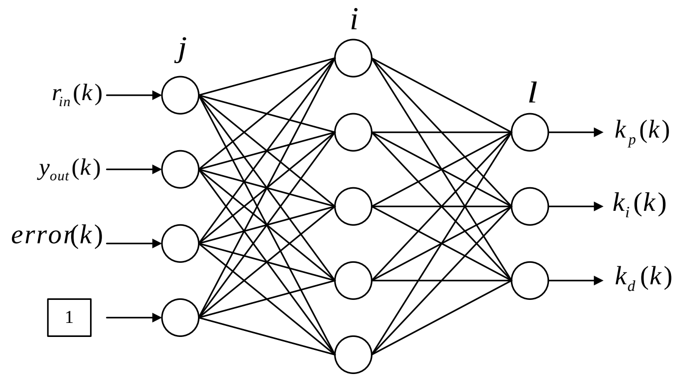


Figure 12. The Structure of BP Neural Network

5.2. Modified BP Learning Algorithm

In order to improve traditional learning BP algorithm, many researchers have been conducted considerable research in recent years and great progress had been made [12]. Usually, optimization algorithm based on numerical method is adopted. This algorithm requires not only the first derivative of objective function, but also the information of second derivative. This is different from gradient descent algorithm adopted by traditional BP neural network [13]. The algorithm can be described by the following formula:

$$\begin{cases} f(X^{(k+1)}) = \min f(X^{(k)} + \alpha^{(k)} S(X^{(k)})) \\ X^{(k+1)} = X^{(k)} + \alpha^{(k)} S(X^{(k)}) \end{cases} \tag{2}$$

where, X^k is a vector constituted by weights and thresholds of network; $S(X^k)$ is search direction of vector space constituted by each component of X; $a(k)$ is the minimal step $f(X(k+1))$ can reach in $S(X^k)$ direction.

The modified BP learning algorithm-conjugate gradient method is adopted in this paper. The fundamental principle of conjugate gradient method is that forming conjugacy in steepest descent direction, and seeking the extreme value of objective function. The first step of realizing conjugate gradient method is searching in negative gradient direction. Then find the conjugate direction and search to get the optimum value fast [14-15]. The vector diagram of conjugate gradient method is shown in Figure 13. The current negative gradient direction is combined linearly with previous direction vector to get a new vector which is named the direction vector of conjugate gradient vector. $g(k)$ is defined as $g(x) = \partial f(x)/\partial x$.

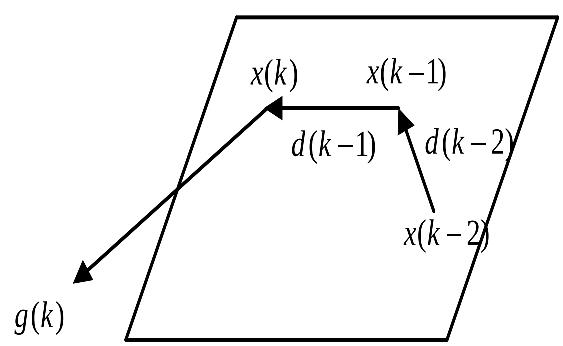


Figure 13. The Vector Diagram of Conjugate Gradient Method

We can analyze the global convergence of conjugate gradient method by using the method Fletcher-Reeves processing non-secondary problem. The value of declining function is increased continually in calculation process of conjugate gradient method. Therefore, the idea of interleave procedure can be introduced, namely make a steepest descent every n steps. The steepest descent method is frequent and anomalous because other steps can not make the objective function increase. So the conjugate gradient method can be guaranteed globally convergent.

Assuming a network with n nodes and L layers, the activation function of this network's hidden nodes adopts Sigmoid function. And the input of every layer nodes is just the output of previous layer; the output of every layer nodes is just provided to the next layer nodes. Usually, the network has only one output in consideration of calculating simply. Assuming N samples (x_k, y_k), $k = 1, 2, ..., N$, the any input, output of any node i and final output of network are respectively represented by x_k, o_{ik} and y_k. Now considering such a condition, when the k-th sample is imported, the input and output of j-th node of l-th layer respectively are:

$$net_{jk}^{l} = \sum_{j} w_{ij}^{l} o_{jk}^{l-1} \tag{3}$$

$$o_{jk}^{l} = f(net_{jk}^{l}) \tag{4}$$

where, o_{jk}^{l-1} represents the output of j-th node of $l-1$ layer when k-th sample is imported.

Error function is as follows:

$$E_k = \frac{1}{2} \sum_{l} (y_{lk} - \overline{y}_{lk})^2 \tag{5}$$

Then

$$\frac{\partial E_k}{\partial w_{ij}^{l}} = \frac{\partial E_k}{\partial net_{yk}^{l}} \frac{\partial net_{yk}^{l}}{\partial w_{ij}^{l}} = \frac{\partial E_k}{\partial net_{yk}^{l}} o_{jk}^{l-1} = \delta_{jk}^{l} o_{jk}^{l-1} \tag{6}$$

We can discuss under two conditions.

②If the j node is output neuron, then

$$o_{jk}^{l} = \overline{y}_{jk} \tag{7}$$

$$\delta_{jk}^{l} = \frac{\partial E_k}{\partial net_{jk}^{l}} = \frac{\partial E_k}{\partial \overline{y}_{jk}} \frac{\partial \overline{y}_{jk}}{\partial net_{jk}^{l}} = -(y_k - \overline{y}_k) f'(net_{jk}^{l}) \tag{8}$$

②If the j node is not output neuron, then

$$\delta_{jk}^{l} = \frac{\partial E_k}{\partial net_{jk}^{l}} = \frac{\partial E_k}{\partial o_{jk}^{l}} \frac{\partial o_{jk}^{l}}{\partial net_{jk}^{l}} = \frac{\partial E_k}{\partial o_{jk}^{l}} f'(net_{jk}^{l}) \tag{9}$$

where, o_{jk}^{l} is the input of $l+1$ layer imported by the output of l layer. When calculating the m-th neuron of $l+1$ layer, we can get:

$$\frac{\partial E_k}{\partial o_{jk}^l} = \sum_m \frac{\partial E_k}{\partial net_{mk}^{l+1}} \frac{\partial net_{mk}^{l-1}}{\partial o_{jk}^l} = \sum_m \frac{\partial E_k}{\partial net_{mk}^{l+1}} w_{mj}^{l+1} = \sum_m \delta_{mk}^{l+1} w_{mj}^{l+1} \tag{10}$$

We can get from the (9) and (10):

$$\delta_{jk}^l = \sum_m \delta_{mk}^{l+1} w_{mj}^{l+1} f'(net_{jk}^l) \tag{11}$$

From (5)-(11), it can be known that:

$$\begin{cases} \delta_{jk}^l = \sum_m \delta_{mk}^{l+1} w_{mj}^{l+1} f'(net_{jk}^l) \\ \dfrac{\partial E_k}{\partial w_{ij}^l} = \delta_{jk}^l O_{jk}^{l-1} \end{cases} \tag{12}$$

The weight correction formula is:

$$\Delta w_k = P_k \lambda_k \tag{13}$$

where, P_k is search direction, λ_k is used to decrease the gradient of search direction.

The search direction P_0 search from the steepest descent direction, namely $P_0 = -g_0$. The search direction of certain point is constituted by weighted quantity of negative gradient of current point and conjugate direction of previous iteration.

$$P_k = -g_k + \beta_{k-1} P_{k-1} \tag{14}$$

where, g_k is the gradient $\nabla E(\omega_k)$ from E to ω_k, β_k is conjugator.

$$\begin{cases} g_k = \dfrac{\partial E_k}{\partial w_{ij}^l} = \delta_{jk}^l O_{jk}^{l-1} \\ \beta_k = \dfrac{g_k^T (g_k - g_{k-1})}{g_{k-1}^T g_{k-1}} \end{cases} \tag{15}$$

Compared with other gradient method, conjugate gradient method can increase convergence speed, improve the effectiveness of algorithm and guarantee the reliability of algorithm [16-17]. It is suit for network with more weights.

5.3. The Structure and Algorithm of Controller

PID controller based on BP network constituted two parts, namely PID controller and BP neural network. The action of classical PID controller is controlling controlled object through closed loop control [18-19]. The three parameters of controller k_p, k_i and k_d are adjusted online and the task of adjusting is accomplished by BP neural network. That is to say, according to real time data of system running $r_{in}(k)$, $y_{out}(k)$ and $error(k)$, the parameters $k_p(k)$, $k_i(k)$ and $k_d(k)$ of PID controller are adjusted by BP algorithm to achieve the structure optimization of performance index. The structure of controller is shown in Figure 14.

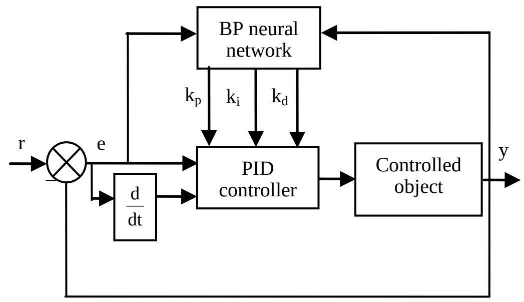


Figure 14. The Structure of PID Controller based on BP Neural Network

The control algorithm is as follo
ws:

①Confirm the structure of BP neural network and give the initial value of weights and learning rate. In details, the node number of input and output layer are confirmed and the value of $w_{ij}^{(1)}(0)$, $w_{li}^{(2)}(0)$ and η are given. At this time $k=1$.

②Get $r_{in}(k)$ and $y_{out}(k)$ through sampling and calculate the error $error(k)=r_{in}(k)-y_{out}(k)$.

③Get the input and output of every layer neuron of BP neural network through calculating and the final output of neural network is recognized as the three adjustable parameters of PID controller $k_p(k)$, $k_i(k)$ and $k_d(k)$.

④According to PID control algorithm, calculate the output of PID controller $u(k)$ and $\Delta u(k)$ through PID parameters $k_p(k)$, $k_i(k)$ and $k_d(k)$.

⑤Through online real-time adjustment of weights $w_{ij}^{(1)}(k)$ and $w_{li}^{(2)}(k)$, adjust the output parameters of PID controller.

⑥Make $k=k+1$, return.

6. The Simulation Results and Analysis

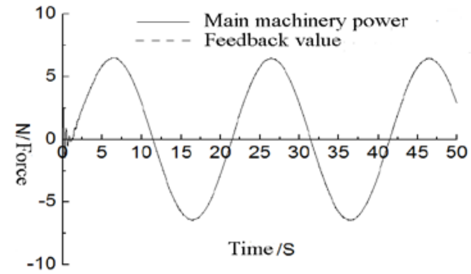
The parameters self-learning PID controller algorithm based on modified BP neural network is used for controller design on time delay simulation platform. The simulation result is shown in Figure 15.

1)The analysis of force tracking

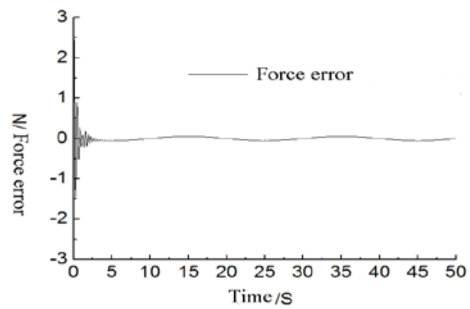
It is can seen from Figure 15 (a) that force tracking performance of master and slave manipulators is good on the whole. The maximal amplitude of force concussion is approximately 2.5 in the beginning and this proved the feasibility of modified BP neural network control algorithm. After adjusting for short time, the slave manipulator begins to track the master manipulator accurately. It is can be seen from the figure that the maximum error is 0.15.

2) The analysis of position tracking

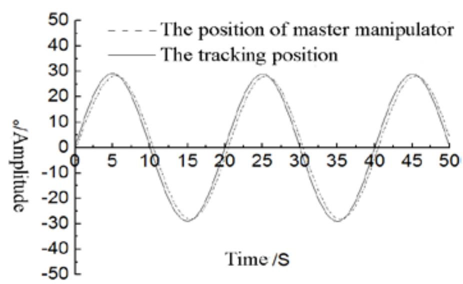
When the master manipulator moves periodically, tracking performance of system is shown in Figure 15 (c). The tracking performance of slave manipulator is stable and the amplitude decay can be ignored. The maximum error is 3.9 and time delay is 0.3s.



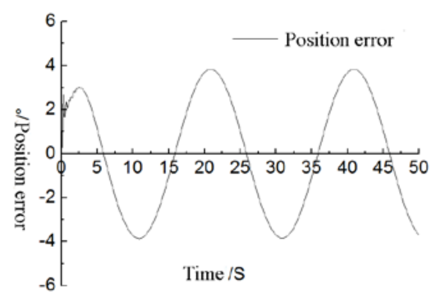
(a) Force tracking curve



(b) Force tracking error curve



(c) Position tracking curve



(d) Position tracking error curve

Figure 15. The Simulation Results

7. Conclusions

In order to decrease the influence of time delay on stability and maneuverability of system, the structure of parameters self-learning PID controller algorithm based on modified BP neural network and modified BP learning algorithm-conjugate gradient method were given in this paper. The controller is constituted by BP neural network and PID controller. Through adjusting the three parameters k_p, k_i and k_d of PID controller online by use of modified BP neural network, the object is controlled by adjusting the output of PID controller. SimMechanics model of 3-DOF manipulator was established in this paper. This model not only reduces the workload that solving the kinetic equation of complex robot system, but also can reflect the real physical model of manipulators more visually and directly. The master and slave manipulators adopt the control structure and principle of bilateral servo control architecture with force deviation feedback. Time delay simulation platform based on TrueTime and Matlab/Simulink software is designed. And the proposed control method is researched on time delay simulation platform. The simulation result shows that force tracking performance of master and slave manipulators is good on the whole, the maximum error is approximately 0.15. The tracking performance of slave manipulator is stable, the maximum error is 3.9 and time delay is approximately 0.3s. This algorithm improves the operability of internet-based tele-operation manipulators system.

Acknowledgements

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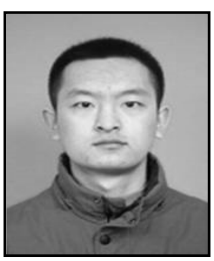

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