Control of Free-floating Space Robotic Manipulators base on Neural Network

ZHANG Wenhui[1] and ZHU Yinfa[2]

**[1] College of Technology, Lishui University
Lishui, 323000, China**

**[2] College of Technology, Lishui University
Lishui, 323000, China**

Abstract

For problems of trajectory tracking of the free-floating space robot model with uncertainties in task space, neural networks adaptive control strategy is put forward by this paper. Because the non-linear system model can not be obtained accurately, neural network is used to directly identify all parts of the system parameters through GL matrix and its multiplication operator "·". Robust controller is designed to eliminate the approximation errors of neural network and external disturbances. The control strategy neither requires an estimate of inverse dynamic model, nor calculates the inverse Jacobin matrix. Global asymptotic stability based on Lyapunov theory is proved by the paper. Simulation results show that higher control precision is achieved. The control strategy has great value in engineering applications.

Keywords: *Neural network, GL matrix, Space robot, Adaptive control, Global asymptotic stability*

1. Introduction

With the development of space technology, space robot will play an important role in space exploration. Owing to the economization of fuel, increase life-span of space robot, and decrease in launch expenditure, positions and attitude of the base are entirely free. Thus there is intense dynamic coupling existing between the manipulator and base. Meanwhile, there are many uncertainties existing in the space robot dynamic model, for example, the dynamic model of manipulator mass, inertia matrix and load quality can not be accurately acquired, and external disturbance signals have a certain impact on the controller.To eliminate these non-linear factors, many advanced control strategies such as robust control [1~3], adaptive control [4]-[5], fuzzy control [6]-[11] and neural network control[12]-[15] have been used in space robot tracking control.

[16]-[17]bring forward adaptive control methods. In the process of designing, the parameters of dynamic equations need be linearized, so complicated pre-calculation is required. [18] proposes an fuzzy-neural control method which does not requires the exact model of robot. But much parameters is adjusted, that affects the real-time. [19] has presented a neural network control method, uncertain model can be identified adaptively by neural network, but this control scheme only can guarantee the system uniformly ultimately bounded (UUB).

For the above shortcomings, this paper presents a neural network adaptive control method. Considering that exact model is difficult to obtain, this control method use the neural network to identify system parameters. robust controller is designed to eliminate the approximation errors of neural network and external disturbances. The control method neither requires an estimate of inverse dynamic model, nor calculates the inverse Jacobian matrix.The amount of calculation is decreased by adopting GL matrix and its multiplication operator. Based on Lyapunov theory, global asymptotic stability of the closed-loop system is proved. Simulation results show that the controller can achieve higher precision.

2. Dynamic Equations of Space Robot in Task Space

Free-floating space robot dynamic equation can be written as follow[20]:

$$M(q)\ddot{q} + B(q,\dot{q})\dot{q} = \tau \tag{1}$$

Where $q, \dot{q}, \ddot{q} \in R^n$ are joint position, velocity and acceleration vectors; $M(q) \in R^{n\times n}$ is symmetric positive definite inertia matrix; $B(q,\dot{q})\dot{q} \in R^{n\times 1}$ is Coriolis/ centrifugal forces; $\tau \in R^{n\times 1}$ is control torque.

As the robot in task is generally given by the cartesian coordinate system. The paper can select the displacement of the robot's end-actuator in Cartesian space as the system output y . Thus the system's augmentation output can be written as:

$$y = h(q) \tag{2}$$

Which $y \in R^n$ indicates the positions and attitudes of the manipulator end-actuator in Cartesian coordinates; for planar two link robot, n = 2. When calculating the derivative of it. The paper can get the following equation:

$$\dot{y} = J(q)\dot{q} \tag{3}$$

In the aboving equation, $J(q) = [J_b(q) \quad J_r(q)]$ represents the Jacobian matrix, $J_b = \partial y / \partial q_b$, $J_r = \partial y / \partial q_r$ .The paper hypothesizes that J_r is a non-singular matrix, and then J is reversible. Thus by the equation (3) and equation (1), taking the external disturbance d into account. The paper finally can obtain the dynamic equation of the space robot in task space:

$$D\ddot{y} + C\dot{y} + d = \tau \tag{4}$$

Where $C = J^{-T}BJ^{-1} - J^{-T}MJ^{-1}\dot{J}J^{-1}$, $D = J^{-T}MJ^{-1}$, $\tau = J^{-T}\tau_q$.

The dynamic equation (4) of space robot in task space has the following properties [21]:

Property1: $D(q)$ is reversible and bounded.

Property2: For any $Z \in R^n$, there is $\frac{1}{2}Z^T\dot{D} = Z^TCZ$.

3. Design of Neural Network Controller

3.1 GL matrix and its Multiplication operators

When the symbol "$\{\cdot\}$" is defined as the GL matrix and "$\cdot$" as its method operator, the GL vector $\{\Theta\}$ and its transpose $\{\Theta\}^T$ may be defined as the following equation:

$$\{\Theta\} = \begin{Bmatrix} \theta_{11} & \theta_{12} & \cdots & \theta_{1n} \\ \theta_{21} & \theta_{22} & \cdots & \theta_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \theta_{n1} & \theta_{n2} & \cdots & \theta_{nn} \end{Bmatrix} = \begin{Bmatrix} \{\theta_1\} \\ \{\theta_2\} \\ \vdots \\ \{\theta_n\} \end{Bmatrix} \tag{5}$$

$$\{\Theta\}^T = \begin{Bmatrix} \theta_{11}^T & \theta_{12}^T & \cdots & \theta_{1n}^T \\ \theta_{21}^T & \theta_{22}^T & \cdots & \theta_{2n}^T \\ \vdots & \vdots & \vdots & \vdots \\ \theta_{n1}^T & \theta_{n2}^T & \cdots & \theta_{nn}^T \end{Bmatrix} \tag{6}$$

For a given GL matrix $\{\Xi\}$

$$\{\Xi\} = \begin{Bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \xi_{n1} & \xi_{n2} & \cdots & \xi_{nn} \end{Bmatrix} = \begin{Bmatrix} \{\xi_1\} \\ \{\xi_2\} \\ \vdots \\ \{\xi_n\} \end{Bmatrix} \tag{7}$$

Then the GL multiplication of $\{\Theta\}^T$ and $\{\Xi\}$ may be defined as a $n \times n$ matrix, as follows:

$$[\{\Theta\}^T \square \{\Xi\}] = \begin{Bmatrix} \theta_{11}^T\xi_{11} & \theta_{12}^T\xi_{12} & \cdots & \theta_{1n}^T\xi_{1n} \\ \theta_{21\xi_{21}}^T & \theta_{22}^T\xi_{22} & \cdots & \theta_{2n}^T\xi_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \theta_{n1}^T\xi_{n1} & \theta_{n2}^T\xi_{n2} & \cdots & \theta_{nn}^T\xi_{nn} \end{Bmatrix} \tag{8}$$

Where, it should be noted that: the GL multiplication should be calculated firstly in the mixed calculation of the matrix and the GL matrix multiplication operator.

3.2 Design of neural network adaptive controller

For the dynamic model (4) of space robot, the paper can define y_r as the reference trajectory, y_d as the ideal trajectory, $e(t)$ as the position tracking error, r as the filtering error slip surface, and $\Lambda \in R^{n\times n}$ as the positive definite matrix, then:

$$\dot{y}_r(t) = \dot{y}_d(t) + \Lambda e(t) \tag{9}$$

$$e(t) = y_d(t) - y(t) \tag{10}$$

$$r(t) = \dot{e}(t) + \Lambda e(t) \tag{11}$$

Lemma[22]: Let $e(t) = h(t) * r(t)$, which $*$ represents convolution, $h(t) = L^{-1}H(s)$ and $H(s)$ is a $n \times n$ class transfer function with strictly exponentially stable, if $r \in L_2^n$, then $e \in L_2^n \cap L_\infty^n$, $\dot{e} \in L_2^n$, e is continuous. When $t \to \infty$, $e \to 0$, $r \to 0$, $\dot{e} \to 0$, the error equation of closed-loop system of free-floating space robot can be writted as:

$$D\dot{r} + Cr = D\ddot{y}_r + C\dot{y}_r + d - \tau \quad (12)$$

If the robot modeling is accurate, and $d = 0$. The paper can design the following control law equation to guarantee the global asymptotic stability of closed-loop system.

$$\tau = D\ddot{y}_r + C\dot{y}_r + K_v r \quad (13)$$

Where K_v represents positive definite matrix.

Proof: to take Lyapunov function as:

$$V = \frac{1}{2} r^T D r \quad (14)$$

To calculate its differential, the paper can obtain the following equation:

$$\dot{V} = r^T D\dot{r} + \frac{1}{2} r^T \dot{D} r \quad (15)$$

To combine the closed-loop error equation (2) and the control law equation (13).the paper can get to the following equation:

$$\dot{V} = -r^T K_v r \le 0 \quad (16)$$

However, in practical engineering, the free-floating space robot model $D(q)$ and $C(q,\dot{q})$ are difficult to accurately obtain, and the external disturbance d exists in system, these nonlinear uncertainties will cause the control performance to degrade.

Considering that the neural network has good nonlinear approximation ability. the paper can adopt RBF local generalization network to approximate the uncertain parts $D(q)$、$C(q,\dot{q})$ in the unknown system. Thus the learning speed can be accelerated greatly and local minimum problems can be avoided. Then the neural network model equation can be written as:

$$\begin{aligned} D(q) &= \sum_l \theta_{ijl}^T \xi_{ijl}(q) + \varepsilon_{dij}(q) \\ &= \theta_{ijl}^T \xi_{ijl}(q) + \varepsilon_{dij}(q) \end{aligned} \quad (17)$$

$$\begin{aligned} C(q,\dot{q}) &= \sum_l \alpha_{ijl}^T \varphi_{ijl}(z) + \varepsilon_{cij}(z) \\ &= \alpha_{ijl}^T \varphi_{ijl}(z) + \varepsilon_{cij}(z) \end{aligned} \quad (18)$$

Where, $z = (q, \dot{q})$, θ_{ijl}, α_{ijl} represents weights of the neural network, $\xi_{ijl}(q)$, $\varphi_{ijl}(z)$ represents radial basis function of the input vector. And $\varepsilon_{dij}(q)$ and $\varepsilon_{cij}(z)$ respectively represents its modeling errors, and is assumed to be bounded.

When using GL matrix and its multiplication operator, $D(q)$ and $C(q,\dot{q})$ can be written as:

$$D(q) = [\{\Theta\}^T \cdot \{\Xi(q)\}] + E_D(q) \quad (19)$$

$$C(q,\dot{q}) = [\{A\}^T \cdot \{Z(z)\}] + E_C(z) \quad (20)$$

Where, $\{\Theta\}$, $\{\Xi(q)\}$, $\{A\}$ and $\{Z(z)\}$ represent the GL matrixes, and their elements respectively are θ_{ijl}, α_{ijl}, $\xi_{ijl}(q)$ and. $\varphi_{ijl}(z)$. $E_D(q)$ and $E_C(z)$ respectively represents the matrix of the modeling errors $\varepsilon_{dij}(q)$ and $\varepsilon_{cij}(z)$.

Where. The paper respectively define $\{\hat{\Theta}\}$ and $\{\hat{A}\}$ as the estimate value of $\{\Theta\}$ and $\{A\}$, and $\{\tilde{\Theta}\}$ and $\{\tilde{A}\}$ as their estimation errors.

$$\{\tilde{\Theta}\} = \{\Theta\} - \{\hat{\Theta}\} \quad (21)$$

$$\{\tilde{A}\} = \{A\} - \{\hat{A}\} \quad (22)$$

Then the controller equation (13) should be revised as:

$$\begin{aligned} \tau = {} & [\{\hat{\Theta}\}^T \cdot \{\Xi(q)\}]\ddot{y}_r + [\{\hat{A}\}^T \cdot \{Z(z)\}]\dot{y}_r \\ & + K_v r + k_s \operatorname{sgn}(r) \end{aligned} \quad (23)$$

Where $k_s > \| E \|, E = E_D \ddot{y}_r + E_C \dot{y}_r + d$ 。

The adaptive law is designed as:

$$\dot{\hat{\theta}}_i = \Gamma_i \cdot \{\xi_i(q)\} \ddot{y}_r r_i \quad (24)$$

$$\dot{\hat{\alpha}}_i = Q_i \cdot \{\varphi_i(z)\} \dot{y}_r r_i \quad (25)$$

Where $\Gamma_i = \Gamma_i^T > 0$, $Q_i = Q_i^T > 0$, $\hat{\theta}_i$ and $\hat{\alpha}_i$ are the vectors of the matrixes whose elements are respectively $\hat{\theta}_{ij}$ and $\hat{\alpha}_{ij}$.

To put the equation (17) and (18) into the equation (4), and combine into the equation (23) .the paper can get to the following equation:

$$\begin{aligned} & \{[\{\Theta\}^T \cdot \{\Xi(q)\}] + E_D(q)\}\ddot{y} + \{[\{A\}^T \cdot \{Z(z)\}] \\ & + E_C(z)\}\dot{y} \\ = {} & [\{\hat{\Theta}\}^T \cdot \{\Xi(q)\}]\ddot{y}_r + [\{\hat{A}\}^T \cdot \{Z(z)\}]\dot{y}_r + K_v r \\ & + k_s \operatorname{sgn}(r) - d \end{aligned} \quad (26)$$

Putting $\dot{y} = \dot{y}_r - r$, $\ddot{y} = \ddot{y}_r - \dot{r}$ into the equation(26), and reducing it. the paper can get to:

$$\begin{aligned} & \{[\{\Theta\}^T \cdot \{\Xi(q)\}] + E_D(q)\}\dot{r} + \{[\{A\}^T \cdot \{Z(z)\}] \\ & + E_C(z)\}r + K_v r + k_s \operatorname{sgn}(r) \\ = {} & [\{\tilde{\Theta}\}^T \cdot \{\Xi(q)\}]\ddot{y}_r + [\{\tilde{A}\}^T \cdot \{Z(z)\}]\dot{y}_r + E \end{aligned} \quad (27)$$

Putting the equation (4) into the aboving equation to calculate, and the paper can obtain the following equation:

$$D\dot{r}+Cr+K_v r+k_s\,\mathrm{sgn}(r) =[\{\tilde{\Theta}\}^T\cdot\{\Xi(q)\}]\ddot{y}_r+[\{\tilde{A}\}^T\cdot\{Z(z)\}]\dot{y}_r+E \quad (28)$$

3.3 Stability Analysis

The paper can define the following Lyapunov functions to prove the stability of closed-loop system.

Proof:

$$V=\frac{1}{2}r^T Dr+\frac{1}{2}\sum_{k=1}^{n}\tilde{\theta}_k^T\Gamma_k^{-1}\tilde{\theta}_k+\frac{1}{2}\sum_{k=1}^{n}\tilde{\alpha}_k^T Q_k^{-1}\tilde{\alpha}_k \quad (29)$$

Then

$$\dot{V}=r^T D\dot{r}+\frac{1}{2}r^T\dot{D}r+\sum_{k=1}^{n}\tilde{\theta}_k^T\Gamma_k^{-1}\dot{\tilde{\theta}}_k+\sum_{k=1}^{n}\tilde{\alpha}_k^T Q_k^{-1}\dot{\tilde{\alpha}}_k \quad (30)$$

In the light of the property (1) and property (2) , the aboving equation can be revised as:

$$\dot{V}=r^T(D\dot{r}+Cr)+\sum_{k=1}^{n}\tilde{\theta}_k^T\Gamma_k^{-1}\dot{\tilde{\theta}}_k+\sum_{k=1}^{n}\tilde{\alpha}_k^T Q_k^{-1}\dot{\tilde{\alpha}}_k \quad (31)$$

Putting the equation (28) into the aboving equation (31).the paper can get to the following equation:

$$\dot{V}=-r^T K_v r-k_s r^T\,\mathrm{sgn}(r)+\sum_{k=1}^{n}\{\tilde{\theta}_k^T\}\{\xi_k(q)\}\ddot{x}_r r_k +\sum_{k=1}^{n}\{\tilde{\alpha}_k^T\}\{\varphi_k(z)\}\dot{x}_r r_k+r^T E+\sum_{k=1}^{n}\tilde{\theta}_k^T\Gamma_k^{-1}\dot{\tilde{\theta}}_k +\sum_{k=1}^{n}\tilde{\alpha}_k^T Q_k^{-1}\dot{\tilde{\alpha}}_k \quad (32)$$

Where

$$r^T[\{\tilde{\Theta}\}^T\cdot\{\Xi(q)\}]\ddot{x}_r=\sum_{k=1}^{n}\{\tilde{\theta}_k^T\}\{\xi_k(q)\}\ddot{x}_r r_k$$

$$r^T\{[\{A\}^T\cdot\{Z(z)\}]\dot{x}_r=\sum_{k=1}^{n}\{\tilde{\alpha}_k^T\}\{\varphi_k(z)\}\dot{x}_r r_k$$

To put the adaptive law equation (24) and the equation (25) into the aboving equation, $k_s>\|E\|$, so the paper can get to the following equation:

$$\dot{V}\le -r^T K_v r\le 0 \quad (33)$$

From (33), and taking $k_s>0|$ into account. The paper can get to $r\in L_2^n$. From the lemma, the paper can derive $e\in L_2^n\cap L_2^\infty$, $\dot{e}\in L_2^n$, in which e is continuous. So when $t\to\infty, e\to 0, r\to 0$ and $\dot{e}\to 0$.

3. Simulation

About the free-floating space robot, the table 1 shows two-DOF space robot simulation parameters. The simulation environment Matlab is 7.0, simulation time is 20S.

Table 1 Parameters of 2-DOF space manipulator

m_0	200 kg	a_1	0.85m
m_1	25 kg	a_2	0.6m
m_2	15 kg	b_0	0.7m
I_0	56 kg m²	b_1	0.85m
I_1	2 kg m²	b_2	0.7m
I_2	1.8 kg m²		

The desired trajectory of the end of space manipulator is:

$\dot{y}_{1d}=1+0.3\cos(\pi t)$ $\dot{y}_{2d}=1+0.3\sin(\pi t)$

The external interferences are:

$f=[q_1 0.1\sin t,\ \ q_2 0.1\sin t]^T$

The filtered tracking error parameters are:

$\Lambda=diag(5,5)$;

The controller gain: $K_v=diag(10,10)$; $k_s=0.4$

The neural network initial weights are 0. the width of all basis functions are 10. The center of basis function is randomly selected in the input and output domain. Hidden nodes are 30 bits. The simulation results are shown in the Figure 2 ~ Figure 4.

The figure 2 shows the tracking scenario map of the position of manipulator's end. The figure 3 shows the neural network approach situation map of the uncertain parts $D(q)$ and $C(q,\dot{q})$ of the space robot. Where the approximate value is its norm number $\|f(\cdot)\|$. The figure 4 shows the situation of the control moment.

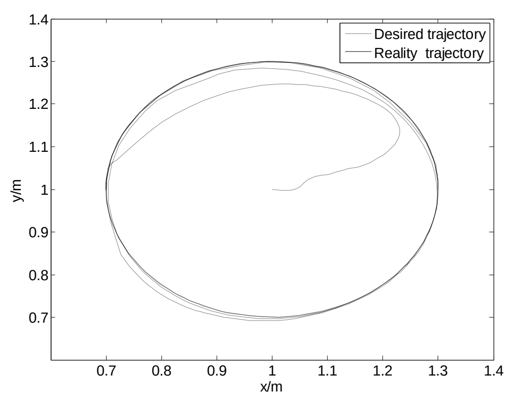
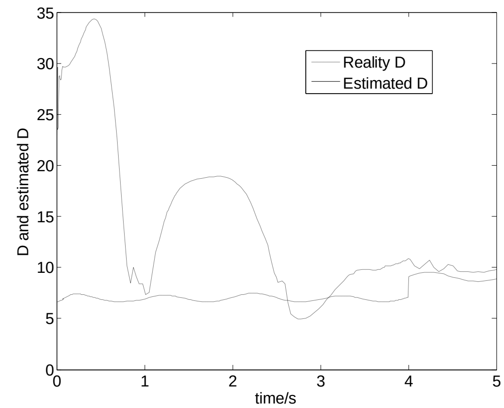
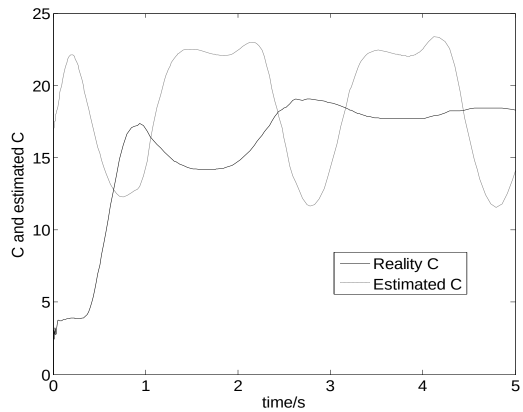


Fig.2 Desire trajectory and real trajectory of end



(a) Estimate value D of neural network and reality value D



(b) Estimate value C of neural network and reality value C

Fig.3 Unknow model and its neural network approach

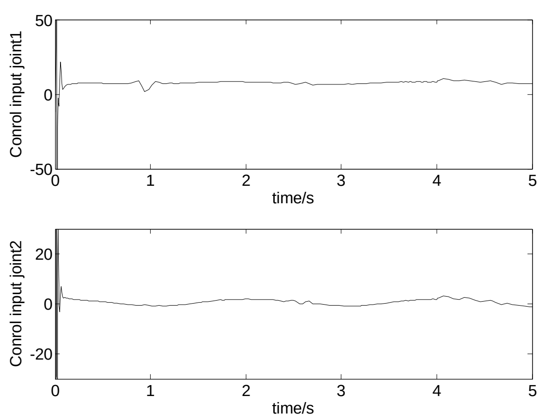


Fig.4 Control torque of two joints

.As can be seen from the Figure 2, the proposed control method can ensure the actual track of the end actuator, and well track the desired trajectory. From the Figure 3.the paper can find that the designed neural network controller may effectively approach unknown model within t = 3S, and at the same time doesn't need great control torque.

The further simulations show that the stronger the system's unknown nonlinearity is, the greater the required control torque is required to achieve better control precision, it is necessary to increase the control torque output. Considering that the space robots usually work under low speed condition in order to maintain their postures, the proposed control method can provide ample time for learning of neural network, and meet fully the requirement of real-time.

4. Conclusion

Aiming at the uncertainty of the free-floating space robot model in task space, this paper puts forward a neural network adaptive control method. this control method obtains control laws bythe utilization of the neural network online modeling technology, the introduction of the GL matrix and its multiplication operator ".", and the parameters through direct identification. The neural network approximation errors and external bounded disturbances are eliminated by sliding mode variable structure controller. The control method neither requires an estimate of inverse dynamic model, nor requires a time-consuming training process. Based on the Lyapunov theory, this control method proves global asymptotic stability of the whole closed-loop system. Simulation results show the neural controller can not only achieve higher precision without calculating the inverse Jacobian matrix, so it reduces the calculation quantity, but also meet real-time requirements. So it has great value in engineering applications.

Acknowledgments

The paper is supported from Zhejiang Provincial Natural Science Foundation of China under Grant No.LY12E05011

References

[1] Dubowsky S ,Papadopoulos E G, "The kinematics, Dynam- ics and control of free-flying space robotic systems". IEEE Trans on Robotics and Automation , Vol.9,No.5,1993,pp. 531 - 543.

[2] REN Y Q , MA B L,"Adaptive Control of Space Robot System Based on Back stepping Design",ACTA AERONAU TICA ET ASTRONAU TICA SINICA, Vol.28,No.2, 2007,pp. 490-494

[3] Cheah C. C, S. Kawamura, Arimoto S, and Lee K, "$H\infty$ Tuning for Task-Space Feedback Control of Robot With Uncertain Jacobian Matrix ", IEEE Trans on Automatic Control, Vol.46,No.8, 2001,pp. 1313-1318.

[4] Kim Y H and Lewis F L, "Neural network output feedback control of robot manipulators", IEEE Trans on Robotics and Automation, Vol.15,No.2, 1999,pp. 301-309.

[5] Gu Y L , Xu Y S, "A normal form augmentation approach to adaptive control of space robot systems", Proc. of the IEEE Int . Conf . on Robotics and Automation , Atlanta , USA , 1993 :731 - 737.

[6] Wang S D, Lin C K, "Adaptive control of robot manipulator using fuzzy compensator ", Fuzzy Sets Syst,

IJCSI International Journal of Computer Science Issues, Vol. 9, Issue 6, No 2, November 2012
ISSN (Online): 1694-0814
www.IJCSI.org

Vol.110,No.3, 2000,pp. 351-363.
[7] Wang C H, Tsai C H, Lin W S, "Robust fuzzy model-following control of robot manipulators", IEEE Trans. Fuzzy Syst, Vol.8,No.4, 2000,pp.462-469.
[8] Lin C K, "Non-singular terminal sliding model control of robot manipulators using fuzzy wavelet networks", IEEE Trans. Fuzzy Syst, Vol.160,No.12, 2009,pp. 1765-1786.
[9] Yoo B K, Ham W C, "Adaptive control of robot manipulator using fuzzy compensator",IEEE Trans.Fuzzy Syst, Vol.8,No.2, 2000,pp. 186-199.
[10] Zhang X D , Jia Q X , Sun H X , Chu M, "The Research of Space Robot Flexible Joint Trajectory Control", Journal of Astronautics. Vol.29,No.6, 2008,pp. 1865-1869. (in Chinese)
[11] Lin C K, "H_∞ reinforcement learning control of robot manipulators using fuzzy wavelet networks", Fuzzy Sets Syst,2009,160(12): 1765 -1786.
[12] Sumit G， Gyanendra K G, "Application of artificial neural engineering and regression models for forecasting shelf life of instant coffee drink", International Journal of Computer Science Issues, Vol.8,No.4, 2011,pp. 320-324
[13] Lewis F L, Kim Y H, "Intelligent optimal control of robotic manipul- ators using neural networks", Automatica, Vol.36,No.9, 2000,pp.1355- 1364.
[14] Psillakis H E, Alexandridis A T, "Adaptive neural motion control of n-link robot manipulators subject to unknown disturbances and stochastic perturbations", Pro. Inst. Electr. Eng, Control Theory Appl, Vol.153,No.2, 2006,pp. 127-138.
[15] Hong Z B, Cheng L, "Self-learning control of space flexible manipulator base on gauss function fuzzy neural network ", engineering mechanics. Vol.29,No.6, 2008,pp. 172-177. (in Chinese)
[16] Chen L, "Adaptive and robust composite control of coordinated motion of space robot system with prismatic joint", Proc.of the 4th World Congress on Intelligent Control and Automation, Shanghai, China,2002,2:1255-1259.
[17] Wang J, Liu L D, Liang B, Wu H-x, "Adaptive Control for Space Manipulators in Task Space", space science technology of China. Vol.12,No.6, 2000,pp. 30-35.
[18] FENG Bao-min,MA Guang-cheng.XIE Wei-nan,WANG Chang-hong, "Design of Intelligent Controller for Space Robot", Journal of Astronautics, Vol.27,No.4, 2006,pp. 730-734.
[19] Xie J , Liu G L , Yan S Z, et al, "Study on Neural Network Adaptive Control Method for Uncertain Space Manipulator", Journal of Astronautics, Vol.31,No.1, 2010,pp. 123-129.
[20] Wei C , Zhao Y, Tian H, " Grasping Control of Space Robot for Capturing Floating Target", ACTA AERONAU TICA ET ASTRONAU TICA SINICA, Vol.31,No.3, 2010,pp. 632-637.
[21] Feng B M,Ma G C, Xie W N,et al, "Design of Intelligent Controller for Space Robot in task space", Journal of Astronautics, Vol.28,No.4, 2007,pp.149-154.
[22] Desoer C, Vidyasagar M, "Feedback systems:input-output properties ", New York:Academic,1975.

ZHANG Wenhui received the B.S and the M.S degree from Harbin Institute of Technology ,Harbin, China, in 2004 and 2008 . He received his Ph.D. degree in Harbin Institute of Technology in 2011. Currently,Dr.zhang has been a School hire associate professor in Lishui University. His papers are Published more than 20 articles.His research interests focus on intelligent control with application to robots.

ZHU Yinfa received the M.S degree from Tongji University in 2004. Currently, he has been an associate professor in Lishui University. His papers are Published more than 30 articles.His research interests focus on neural network control and fuzzy cotrol.