DYNAMIC FOR DUAL-ARM FLOATING SPACE ROBOT WITH CLOSED-CHAIN AND RECURRENT ROBUST FUZZY NEURAL NETWORK FOR OBJECT GRASPING

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ABSTRACT

The dynamic model and the control method for dual-arm space robot grasping a target are discussed. Based on the Lagrange method, the dynamic model of an open chain space robot is established.The dynamics equations of dual-arm space robot with closed-chain are derived by incorporating the closed-loop constraints equations into equation of open chain system. Upon this basis, the recurrent robust fuzzy neural network control is proposed for the closed-chain system with uncertain parameters to complete the accurate control of load position and attitude. The recurrent fuzzy neural network is used to approximate the unknown part with H_∞ tracking characteristic to overcome the effects caused by system parameter perturbation. At last, numerical examples simulate the process of a planar dual-arm space robot transferring a target and verify the efficiency of the control scheme.

1 INTRODUCTION

With the development of space technology, there has been much interest in the space robot[1-2] recently. The space robot system has been used in the space missions such as the surviving, construction, repair and maintenance of satellites and space stations. The free-floating space is a special kind of space manipulator which the base is free under the micro-gravity space environment. For the dynamic coupling between the manipulator and the base of the free floating space manipulator, the trajectory control of a space robot is more complicated than that of a terrestrial robotic system, and the situation will be worse when some of system inertial parameters are uncertain[3]. Walker et al.[4] proposed adaptive control for space robot with uncontrolled position and attitude of base. Chen et al.[5] proposed robust control methods for a space robot system with uncertain parameters were estimated on-line. Over the last ten years, many control scheme studies has been applied in space robot, such as adaptive fuzzy control[6],neural network control[7], etc. Most of the space robot researches mainly focuse on the control of single arm space robot, the control of dual-arm space robot research is less. And none of the aforementioned studies has been performed against the closed-loop constraints of a dual-arm space robot. This is because the closed chain dual-arm space robot has some problems: (1) the closed chain grasping system introduces closed-loop constraint; (2) closed chain system controllers are redundancy and need distribution torques reasonably.

Since the heavy load and task complexity is growing up in space mission, multi-arm systems become more and more important in future. The closed-loop configuration will be formed when the manipulator arms grasp a common target. The closed-loop constraints imposes both kinematic and dynamic problem on the space robot system. Because the aforementioned problem, the control scheme design for dual-arm space robot grasping a target will be more complicated than that for the unconstrained one. Dual-arm space robot have been applied some effective works on the tracking control with open chain[8]. Wang et al.[9] developed a robust control method for closed chain dual-arm space robot; however, the system need feedback force information of end-effector.

This paper studies the tracking control scheme of a dual-arm space robot to manipulate a target. The dynamic equations of open chain dual-arm space robot are derived by applying the Lagrange equations. With the closed-loop constraints equations, the reduced-order equations of the dual-arm space robot with closed-chain are obtained. Based on the dynamic model, a recurrent robust fuzzy neural network control is proposed for control the position and attitude of the base and load. The uncertain part is approximated by neural network on-line, and H_∞ robust item is used to overcome the approximation error. Global asymptotic stability is proven by using Lyapunov's method. The numerical simulations show the effectiveness of the proposed control scheme.

2 SYSTEM DYNAMICS AND KINEMATICS ANALYSIS OF DUAL-ARM SYSTEM

The planar space robot consists of a free-floating base and two rigid manipulators, as shown in Fig1. Choosing origin O is located at an arbitrary point in planar, the inertia coordinate inertial coordinate frames XOY is built. Choosing the local frame coordinate of base and each link $x_iO_iy_i$ $(i=1,2,\cdots,6)$. O_0 、 O_m are the mass center of base and load. O_i $(i=1,2,\cdots,6)$ is the mass center of each link. O_m is on the line connection between O_3 and O_6 . l_i $(i=1,2,\cdots,6)$, the length of O_0 O_1 and O_0 O_4 are d_0 .The distance of mass center of load O_m to end-effector are d_L and d_R . The dual-arm space robot forms a closed-chain after the capture operation.

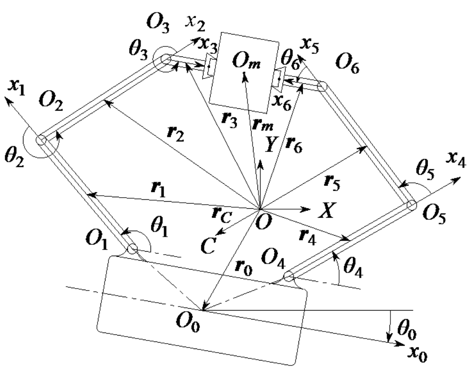

Figure1: Structure of dual-arm space robot with closed chain

2.1 Kinematics and dynamics analysis of open chain system

The dual-arm space robot with closed-chain is virtual disconnect at point b , and the irtual unconstrained system is shown in Fig1. I_i is the rotational inertia of each part, m_i is quality of each part. x_0 、 y_0 are mass center coordinates of base.

The generalized coordinates matrix of open chain system is defined as:

$$\boldsymbol{q}=[x_0 \quad y_0 \quad \theta_0 \quad \boldsymbol{\theta}_L^{\mathrm{T}} \quad \boldsymbol{\theta}_R^{\mathrm{T}}]^{\mathrm{T}} \tag{1}$$

where $\boldsymbol{\theta}_L=\begin{bmatrix}\theta_1 & \theta_2 & \theta_3\end{bmatrix}^{\mathrm{T}}$ denotes corners of left arm, $\boldsymbol{\theta}_R=\begin{bmatrix}\theta_4 & \theta_5 & \theta_6\end{bmatrix}^{\mathrm{T}}$ denotes corners of left arm, θ_0 is the attitude of base, system has nine degrees of freedom.

The dynamic equations of dual-arm space robot with open chain is obtained by the Lagrange equations

$$\boldsymbol{M}\begin{pmatrix}\ddot{x}_0\\ \ddot{y}_0\\ \ddot{\theta}_0\\ \ddot{\boldsymbol{\theta}}_L\\ \ddot{\boldsymbol{\theta}}_R\end{pmatrix}+\boldsymbol{H}\begin{pmatrix}\dot{x}_0\\ \dot{y}_0\\ \dot{\theta}_0\\ \dot{\boldsymbol{\theta}}_L\\ \dot{\boldsymbol{\theta}}_R\end{pmatrix}=\boldsymbol{\tau} \tag{2}$$

$\boldsymbol{\tau}$ is the generalized control torque , For the convenience of description, system dynamic equations

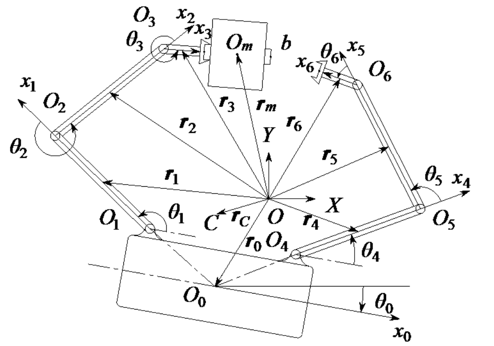

Figure2: Structure of unconstrained dual-arm space robot

is rewritten as:

$$\boldsymbol{M}\ddot{\boldsymbol{q}}+\boldsymbol{H}\dot{\boldsymbol{q}}=\boldsymbol{\tau} \tag{3}$$

where $\boldsymbol{M}\in\boldsymbol{R}^{9\times 9}$ a symmetric positive definite system inertia matrix. $\boldsymbol{H}\dot{\boldsymbol{q}}\in\boldsymbol{R}^{9\times 1}$ is a vector of the centripetal and coriolis factors. For arbitrary $\boldsymbol{x}\in\boldsymbol{R}^{9\times 1}$, it satisfies that[10]:

$$\boldsymbol{x}^{\mathrm{T}}(\dot{\boldsymbol{M}}-2\boldsymbol{H})\boldsymbol{x}=0 \tag{4}$$

$\dot{\boldsymbol{M}}-2\boldsymbol{H}$ is skew symmetric.

2.2 Kinematics and dynamics analysis of closed-chain system

The dynamic equations of reduced-order form for the closed-chain system will be established in this section. Selecting a motion reference point b at the cutting surface. The motion reference points have same position and speed in inertial frame and body-fixed coordinate system.

According to open chain system of geometric relations, the position vectors from motion reference points to O_0 are given as:

$$\begin{cases}\boldsymbol{r}_{0L}=\left(x_{0L} \quad y_{0L}\right)\\ \boldsymbol{r}_{bL}=\boldsymbol{r}_{0L}+l_1\boldsymbol{e}_{01}+l_2\boldsymbol{e}_{02}+(d_3+d_L+d_R)\boldsymbol{e}_{03}\\ \boldsymbol{r}_{0R}=\left(x_{0R} \quad y_{0R}\right)\\ \boldsymbol{r}_{bR}=\boldsymbol{r}_{0R}+l_4\boldsymbol{e}_{04}+l_5\boldsymbol{e}_{05}+d_6\boldsymbol{e}_{06}\end{cases} \tag{5}$$

$\boldsymbol{r}_{0L}$ and $\boldsymbol{r}_{0R}$ are position vectors from O_1 and O_4 to O_0 in base-fix coordinate, $\boldsymbol{e}_{0i}$ is base vector.

Depending on the characters of motion reference points, thus

$$\boldsymbol{N}_L\dot{\boldsymbol{\theta}}_L=\boldsymbol{N}_R\dot{\boldsymbol{\theta}}_R \tag{6}$$

Let

$$\boldsymbol{U}=[\boldsymbol{I}_{6\times 6} \quad \boldsymbol{U}_1^{\mathrm{T}}] \tag{7}$$

$$\boldsymbol{U}_1 = [\boldsymbol{O}_{3\times3} \quad \boldsymbol{N}_R^{-1}\boldsymbol{N}_L] \tag{8}$$

$\boldsymbol{I}_{n\times n}$ is a $n\times n$ unit matrix, $\boldsymbol{O}_{n\times n}$ is a $n\times n$ zero matrix.

The generalized coordinates matrix of closed-chain system is defined as:

$$\boldsymbol{q}_f = [x_0 \quad y_0 \quad \theta_0 \quad \boldsymbol{\theta}_L^{\mathrm{T}}] \tag{9}$$

According to Eq.(9), Eq. (10), Eq. (11)and Eq. (12), can get:

$$\dot{\boldsymbol{q}} = U\dot{\boldsymbol{q}}_f \tag{10}$$

Differentiating Eq. (10), we have

$$\ddot{\boldsymbol{q}} = \boldsymbol{U}^{\mathrm{T}}\ddot{\boldsymbol{q}}_f + \dot{\boldsymbol{U}}^{\mathrm{T}}\dot{\boldsymbol{q}}_f \tag{11}$$

Substituting Eq.(10), Eq.(11) into Eq.(3), the dynamic equations of closed-chain are obtained as follow:

$$\bar{\boldsymbol{M}}\ddot{\boldsymbol{q}}_f + \bar{\boldsymbol{H}}\dot{\boldsymbol{q}}_f = \bar{\boldsymbol{\tau}} \tag{12}$$

where

$$\bar{\boldsymbol{M}} = \boldsymbol{UMU}^{\mathrm{T}} \tag{13}$$

$$\bar{\boldsymbol{H}} = \boldsymbol{U}[\boldsymbol{HU}^{\mathrm{T}} + \boldsymbol{M}\dot{\boldsymbol{U}}^{\mathrm{T}}] \tag{14}$$

$$\bar{\boldsymbol{\tau}} = \boldsymbol{U\tau} \tag{15}$$

In the dynamic equations of closed-chain system, For arbitrary $\boldsymbol{y} \in R^{6\times1}$, $\bar{\boldsymbol{M}} \in \boldsymbol{R}^{6\times6}$ 、 $\bar{\boldsymbol{H}} \in \boldsymbol{R}^{6\times6}$ still satisfy that:

$$\boldsymbol{y}^{\mathrm{T}}(\dot{\bar{\boldsymbol{M}}} - 2\bar{\boldsymbol{H}})\boldsymbol{y} = 0 \tag{16}$$

$\dot{\bar{\boldsymbol{M}}} - 2\bar{\boldsymbol{H}}$ is skew symmetric.

So far, we have obtain the dynamic equations of closed-chain system.

3 RECURRENT ROBUST FUZZY NEURAL NETWORK CONTROL

3.1 Recurrent robust fuzzy neural network

The four-layer recurrent fuzzy neural network[11] is shown in fig2.

Input layer

$$In_i^{(1)} = Out_i^{(1)} = x_i \ (i = 1,2,...,m) \tag{17}$$

Superscript means the which layer the input and output belong to.

Member function layer:

$$Out_{ij}^{(2)} = \mu(Out_i^{(1)}) = e^{-[(Out_i^{(1)} - a_{ij}^2)/b_{ij}^2]} \tag{18}$$

Fuzzy reasoning layer:

$$Out_k^{(3)} = \prod w_{jk} In_j^{(3)} w_k Out_{k-1}^{(3)} \ (k = 1,2,...,l) \tag{19}$$

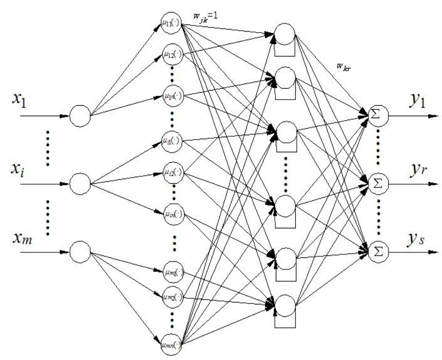

Figure3: Structure of recurrent fuzzy neural network

Output layer, the layer of defuzzification:

$$y_r = Out_r^{(4)} = w_{kr} In_k^{(4)} \ (r = 1,2,...,s) \tag{20}$$

Output can be written as follow:

$$u = \boldsymbol{W}_r^{\mathrm{T}}\boldsymbol{\Phi} \tag{21}$$

3.2 Control design of closed chain system

In order to control the position and attitude of both the base and the load, the output matrix of system is defined as:

$$\boldsymbol{X} = \begin{bmatrix} x_0 & y_0 & \theta_0 & x_{\mathrm{m}} & y_{\mathrm{m}} & \theta_{\mathrm{m}} \end{bmatrix}^{\mathrm{T}} \tag{22}$$

Differentiating the Eq.(22):

$$\dot{\boldsymbol{X}} = \boldsymbol{J}_0(\boldsymbol{q}_{\mathrm{f}})\dot{\boldsymbol{q}}_{\mathrm{f}} \tag{23}$$

$\boldsymbol{J}_0(\boldsymbol{q}_f) \in \boldsymbol{R}^{6\times6}$ is the Jacobian matrix.

Defining the output error as follow:

$$\boldsymbol{e} = \boldsymbol{X}_{\mathrm{d}} - \boldsymbol{X} \tag{24}$$

With Eq.(24), the dynamic equations of closed-chain system can be rewritten as:

$$\boldsymbol{M}_{\mathrm{X}}\ddot{\boldsymbol{X}} + \boldsymbol{H}_{\mathrm{X}}\dot{\boldsymbol{X}} = \bar{\boldsymbol{\tau}} \tag{25}$$

wherer $\boldsymbol{M}_{\mathrm{X}} = \bar{\boldsymbol{M}}\boldsymbol{J}_0^{-1}$, $\boldsymbol{H}_{\mathrm{X}} = \bar{\boldsymbol{H}}\boldsymbol{J}_0^{-1} - \bar{\boldsymbol{M}}\boldsymbol{J}_0^{-1}\dot{\boldsymbol{J}}_0\boldsymbol{J}_0^{-1}$ 。

Since the uncertain parameters of system, we can get:

$$\hat{\boldsymbol{M}}_{\mathrm{X}}\ddot{\boldsymbol{X}} + \hat{\boldsymbol{H}}_{\mathrm{X}}\dot{\boldsymbol{X}} + \boldsymbol{f}(\boldsymbol{\delta}) = \bar{\boldsymbol{\tau}} \tag{26}$$

where $\hat{\boldsymbol{M}}_{\mathrm{X}}$ 、 $\hat{\boldsymbol{H}}_{\mathrm{X}}$ is nominal model, $\Delta\boldsymbol{M}_{\mathrm{X}}$ 、 $\Delta\boldsymbol{H}_{\mathrm{X}}$ is model error, and $f(\boldsymbol{\delta}) = \Delta\boldsymbol{M}_{\mathrm{X}}\ddot{\boldsymbol{X}} + \Delta\boldsymbol{H}_{\mathrm{X}}\dot{\boldsymbol{X}}$ 。

Using recurrent fuzzy neural network to approximate the unknown part $f(\boldsymbol{\delta})$ as follow:

$$f(\boldsymbol{\delta}) = \boldsymbol{W}^{*\mathrm{T}}\boldsymbol{\Phi} + \Delta\boldsymbol{\delta} \tag{27}$$

where $\boldsymbol{W}^*$ is the optimal weight matrix. $\boldsymbol{\Phi}$ is a column correlation with primary function, $\Delta\boldsymbol{\delta}$ is approximate error.

For the uncertain parameters space robot, design the control as follow:

$$\boldsymbol{\tau} = \hat{\boldsymbol{M}}_{\mathrm{X}}(\ddot{\boldsymbol{X}}_{\mathrm{d}} + \boldsymbol{K}_{\mathrm{v}}\dot{\boldsymbol{e}} + \boldsymbol{K}_{\mathrm{p}}\boldsymbol{e}) + \hat{\boldsymbol{H}}_{\mathrm{X}}\dot{\boldsymbol{X}} + \boldsymbol{W}^{\mathrm{T}}\boldsymbol{\Phi} + \boldsymbol{\mu} \tag{28}$$

$\boldsymbol{\mu}$ is Robust control term， which is used to eliminate the approximate error.

With Eq.(28) and Eq.(25), we have:

$$\hat{\boldsymbol{M}}_{\mathrm{X}}(\ddot{\boldsymbol{e}} + \boldsymbol{K}_{v}\dot{\boldsymbol{e}} + \boldsymbol{K}_{p}\boldsymbol{e}) - \tilde{\boldsymbol{W}}^{\mathrm{T}}\boldsymbol{\Phi} - \Delta\boldsymbol{\delta} + \boldsymbol{\mu} = 0 \tag{29}$$

where $\tilde{\boldsymbol{W}} = \boldsymbol{W}^* - \boldsymbol{W}$.

Denote $\boldsymbol{Y} = [\boldsymbol{y}_1^{\mathrm{T}} \quad \boldsymbol{y}_2^{\mathrm{T}}] = [\boldsymbol{e}^{\mathrm{T}} \quad \dot{\boldsymbol{e}}^{\mathrm{T}}]^{\mathrm{T}}$, we have：

$$\begin{cases} \dot{\boldsymbol{y}}_1 = \boldsymbol{y}_2 \\ \dot{\boldsymbol{y}}_2 = -\boldsymbol{K}_{\mathrm{p}}\boldsymbol{y}_1 - \boldsymbol{K}_{\mathrm{v}}\boldsymbol{y}_2 + (\ddot{\boldsymbol{e}} + \boldsymbol{K}_{\mathrm{v}}\dot{\boldsymbol{e}} + \boldsymbol{K}_{\mathrm{p}}\boldsymbol{e}) \end{cases} \tag{30}$$

The system state space equations can be written as:

$$\dot{\boldsymbol{Y}} = \boldsymbol{A}\boldsymbol{Y} + \boldsymbol{B}\hat{\boldsymbol{M}}_{\mathrm{X}}^{-1}(\tilde{\boldsymbol{W}}^{\mathrm{T}}\boldsymbol{\Phi} + \Delta\boldsymbol{\delta} - \boldsymbol{\mu}) \tag{31}$$

where $\boldsymbol{A} = \begin{bmatrix} \boldsymbol{0} & \boldsymbol{I}_{6\times6} \\ -\boldsymbol{K}_{\mathrm{p}} & -\boldsymbol{K}_{\mathrm{v}} \end{bmatrix}$， $\boldsymbol{B} = \begin{bmatrix} \boldsymbol{0}_{6\times6} \\ \boldsymbol{I}_{6\times6} \end{bmatrix}$， The approximation errors of the system can be regard as external disturbance, and $\boldsymbol{\Xi} = \hat{\boldsymbol{M}}_{\mathrm{X}}^{-1}\Delta\boldsymbol{\delta} \in L_2[0,\infty)$， there is a positive constant $\boldsymbol{O}_{\delta}$ let $\int_0^{\infty}\left\|\hat{\boldsymbol{M}}_{\mathrm{X}}^{-1}\Delta\boldsymbol{\delta}\right\|^2 dt \le \boldsymbol{O}_{\delta}$ 。

Robust item is designed as follow:

$$\boldsymbol{\mu} = \hat{\boldsymbol{M}}_{\mathrm{X}}\boldsymbol{R}^{-1}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{y} \tag{32}$$

$\boldsymbol{R} = \boldsymbol{R}^{\mathrm{T}}$ is gain matrix, positive definite matrix $\boldsymbol{P}$ satisfy the Riccati equation:

$$\boldsymbol{P}\boldsymbol{A} + \boldsymbol{A}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{B}(\frac{1}{\omega^2}\boldsymbol{I}_{3\times3} - 2\boldsymbol{R}^{-1})\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P} = -\boldsymbol{Q} \tag{33}$$

where ω is disturbance attenuation index $\boldsymbol{Q}$ is positive definite matrix

Choosing the weights of the adaptive law as follow：

$$\dot{\boldsymbol{W}} = \boldsymbol{\Lambda}^{-1}\boldsymbol{\Phi}\boldsymbol{y}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{B}\hat{\boldsymbol{M}}_{\mathrm{X}}^{-1} \tag{34}$$

To verify the stability and H_{∞} tracking characteristics of the system， the Lyapunov function is defined as follow:

$$V = \frac{1}{2}\boldsymbol{y}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{y} + \frac{1}{2}\mathrm{tr}(\tilde{\boldsymbol{W}}^{\mathrm{T}}\boldsymbol{\Lambda}\tilde{\boldsymbol{W}}) \tag{35}$$

Differentiating Eq.(35)

$$\begin{aligned} \dot{V} &= \frac{1}{2}\dot{\boldsymbol{y}}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{y} + \frac{1}{2}\boldsymbol{y}^{\mathrm{T}}\boldsymbol{P}\dot{\boldsymbol{y}} + \frac{1}{2}\mathrm{tr}(\tilde{\boldsymbol{W}}^{\mathrm{T}}\boldsymbol{\Lambda}\dot{\tilde{\boldsymbol{W}}}) \\ &= \frac{1}{2}\left[\boldsymbol{A}\boldsymbol{y} + \boldsymbol{B}\hat{\boldsymbol{M}}_{\mathrm{X}}^{-1}(\tilde{\boldsymbol{W}}\boldsymbol{\Phi} + \Delta\boldsymbol{\delta} - \boldsymbol{\mu})\right]^{\mathrm{T}}\boldsymbol{P}\boldsymbol{y} + \\ &\quad \frac{1}{2}\boldsymbol{y}^{\mathrm{T}}\boldsymbol{P}\left[\boldsymbol{A}\boldsymbol{y} + \boldsymbol{B}\hat{\boldsymbol{M}}_{\mathrm{X}}^{-1}(\tilde{\boldsymbol{W}}\boldsymbol{\Phi} + \Delta\boldsymbol{\delta} - \boldsymbol{\mu})\right] + \mathrm{tr}(\tilde{\boldsymbol{W}}^{\mathrm{T}}\boldsymbol{\Lambda}\dot{\tilde{\boldsymbol{W}}}) \\ &= \frac{1}{2}\boldsymbol{y}^{\mathrm{T}}[\boldsymbol{P}\boldsymbol{A} + \boldsymbol{A}^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{B}(\frac{1}{\omega^2}\boldsymbol{I}_{3\times3} - 2\boldsymbol{R}^{-1})\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P}]\boldsymbol{y} - \\ &\quad \frac{1}{2}(\frac{1}{\omega}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{y} - \omega\boldsymbol{\Xi})^{\mathrm{T}}(\frac{1}{\omega}\boldsymbol{B}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{y} - \omega\boldsymbol{\Xi}) + \frac{1}{2}\omega^2\boldsymbol{\Xi}^{\mathrm{T}}\boldsymbol{\Xi} \\ &\le -\frac{1}{2}\boldsymbol{y}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{y} + \frac{1}{2}\omega^2\boldsymbol{\Xi}^{\mathrm{T}}\boldsymbol{\Xi} \end{aligned} \tag{36}$$

Integrating Eq.(36) from 0 to T :

$$V(\mathrm{T}) - V(0) \le -\frac{1}{2}\int_0^{\mathrm{T}}\boldsymbol{y}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{y} + \frac{1}{2}\omega^2\int_0^{\mathrm{T}}\boldsymbol{\Xi}^{\mathrm{T}}\boldsymbol{\Xi}dt \tag{37}$$

Cause $V(T) \ge 0$, we have:

$$\frac{1}{2}\int_0^{\mathrm{T}}\boldsymbol{y}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{y} \le V(0) + \frac{1}{2}\omega^2\int_0^{\mathrm{T}}\boldsymbol{\Xi}^{\mathrm{T}}\boldsymbol{\Xi}dt$$

So the system tracking errors satisfy $H\infty$ tracking characteristics of the system.

$\bar{\boldsymbol{\tau}}$ and $\boldsymbol{\tau}$ can be rewritten as:

$$\bar{\boldsymbol{\tau}} = [\bar{\boldsymbol{\tau}}_a^{\mathrm{T}} \quad \bar{\boldsymbol{\tau}}_b^{\mathrm{T}}]^{\mathrm{T}} \tag{38}$$

$$\boldsymbol{\tau} = [\boldsymbol{\tau}_o^{\mathrm{T}} \quad \boldsymbol{\tau}_L^{\mathrm{T}} \quad \boldsymbol{\tau}_R^{\mathrm{T}}]^{\mathrm{T}} \tag{39}$$

From the preview derivation process, we have:

$$\bar{\boldsymbol{\tau}}_o = \bar{\boldsymbol{\tau}}_a \tag{40}$$

$$\begin{bmatrix} \boldsymbol{\tau}_L \\ \boldsymbol{\tau}_R \end{bmatrix} = \boldsymbol{E}\boldsymbol{\Omega}^{\mathrm{T}}\left(\boldsymbol{\Omega}\boldsymbol{E}\boldsymbol{\Omega}^{\mathrm{T}}\right)^{-1}\bar{\boldsymbol{\tau}}_{\mathrm{b}} \tag{41}$$

Where , $\boldsymbol{E}$ is gain matrix, $\boldsymbol{\Omega} = [\boldsymbol{I}_{3\times3} \quad (\boldsymbol{N}_R^{-1}\boldsymbol{N}_L)^{\mathrm{T}}]$.

4 NUMERICAL SIMULATION

A planar free-floating dual-arm space robot system is experimentally simulated by using the proposed controller. The physical parameters of . The physical parameters of closed-chain system are defined as $d_0 = 1.062\mathrm{m}$, $d_{\mathrm{L}} = 0.5\mathrm{m}$, $d_{\mathrm{R}} = 0.5\mathrm{m}$, $l_i = 2\mathrm{m}$ $(i = 1,2,4,5)$, $l_j = 0.5\mathrm{m}$ $(\mathrm{j} = 3,6)$, $m_0 = 200\mathrm{kg}$, $m_{\mathrm{m}} = 50\mathrm{kg}$, $m_i = 20\mathrm{kg}$ $(i = 1,2,4,5)$, $m_j = 5\mathrm{kg}$ $(j = 3,6)$, $I_0 = 50\mathrm{kg}\cdot\mathrm{m}^2$, $I_{\mathrm{m}} = 10\mathrm{kg}\cdot\mathrm{m}^2$, $I_i = 10\mathrm{kg}\cdot\mathrm{m}^2$ $(i = 1,2,4,5)$, $I_j = 2\mathrm{kg}\cdot\mathrm{m}^2$ $(j = 3,6)$.

The initial state of base and load is:

$$\boldsymbol{X} = \left[0.3\text{m} \quad 0.3\text{m} \quad 10^\circ \quad 0.5224\text{m} \quad 3.5753\text{m} \quad -10^\circ\right]^{\mathrm{T}}$$

The desired state of base and load is：

$$\boldsymbol{X}_d = [0\text{m} \quad 0\text{m} \quad 0^\circ \quad 0\text{m} \quad 3\text{m} \quad 0^\circ]^{\mathrm{T}}\text{。}$$

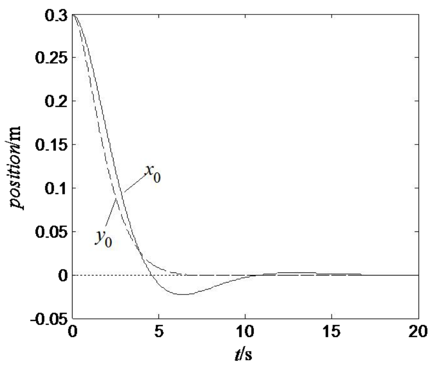

Figure4: Position tracking of base

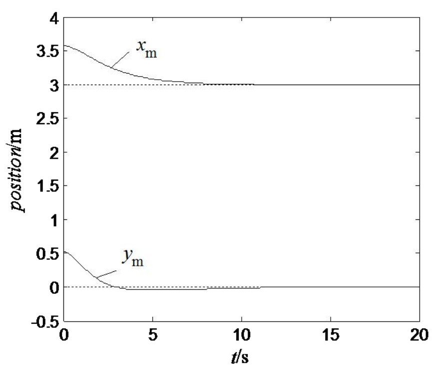

Figure5: Position tracking of load

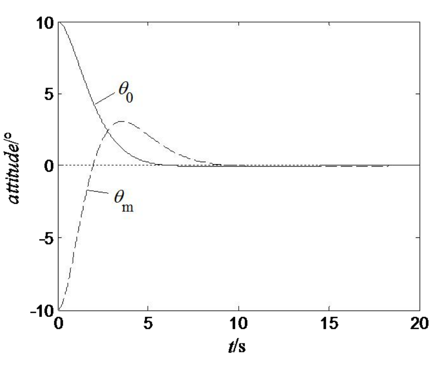

Figure6: Attitude tracking of base and load

Fig.4-6 show the position and attitude of load and base reach the specified location and be stable. These mean that use the proposed control method, the dual-arm space robot could finish the task precisely.

5 CONCLUSION

In this paper, the dynamics and kinematics of dual-arm space robot with closed-chain during transfer a target process is analyzed by closed-loop constraint equations and the Lagrange equation. The proposed control method can be extended to muti-arm and muti-link space robot system. The control scheme dispense with accurate system model or linear parameterization of the system dynamic equations.

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