IMPACT DYNAMIC MODELING FOR DUAL-ARM SPACE ROBOT CAPTURING NON-COOPERATIVE SPACECRAFT AND DECENTRALIZED ADAPTIVE FUZZY ROBUST CONTROL FOR CLOSED CHAIN

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ABSTRACT

The impact effect analysis for a dual-arm space robot capturing a non-cooperative spacecraft and the coordinated stabilization control problem for unstable closed chain system are discussed. At first, the dynamic equations of dual-arm space robot and spacecraft are obtained by multi-body theory. The closed chain combined system is derived by momentum conservation law and closed chain geometric constraints; the response of the dual-arm space robot impacted by the target is analyzed at the same time. Secondly, the decentralized control is designed for unstable closed chain system. The combined system is decomposed into generalized linear subsystems by feedback linearization theory. Adaptive fuzzy H_∞ robust control schemes are designed for each subsystem to eliminate the effect of interconnections and the unknown part. Each subsystem control signal independently of each other, reducing the computation. Cooperative operation between manipulators is guaranteed by using weighted minimum-norm theory to distribute torques. At last, numerical examples simulate the process of collision and verify the efficiency of the control scheme.

1 INTRODUCTION

The document is printed in two columns. Since the 80s, more and more space robot is applied to complete the space mission, such as Canada arm, JEMRMS and ERA[1]. These space robot systems help human beings to accomplish many dangerous space activities, such as building up the international space station, maintain the space vehicle, eliminating the space garbage and so on. And these systems are single arm space robot. In order to improve the loading ability and motion accuracy of space robot, the development trend of space robot system is from single arm system to dual arm system. In the process of space mission, the impact between the manipulator end effectors and the target is inevitable. In the situation of micro-gravity space environment, there will be large angle reversal of the unstable system, can cause damage to the space facilities. Single arm space robot has a lot of theoretical result[2-3]; the research of dual-arm space robot system is less than single arm system, especially in the process of capturing non-cooperative spacecraft by dual-arm system. The closed-loop configuration will be formed when the manipulator arms grasp a common target. The closed chain system introduces closed-loop constraint.

Many research work of the dual-arm space robot capture operation control focus on the pre-impact phase. Chen et al.[4] builds the dynamic of space robot with dual-arm with open chain, and applying the sliding mode mode control scheme to perform the trajectory tracking. The impact between the manipulator end effector will affect he free floating space robot steady state in space[5],whose manipulator and base are coupling in dynamic equation[6]. Sashida et al.[7] derivate the impact model by extended inertia tensor concept. Yoshida et al.[8] find out the optimal space manipulator configurations to reduce the effect of impact between space robot and target based on reaction null-space concept.

In this paper, the impact dynamics is obtained by multi-body system and closed-loop constraints equations. The effect of impact during the composite system capture a target is analyzed based on the principle of conservation of momentum. The combined system is decomposed into generalized linear subsystems by feedback linearization theory. An adaptive controller is designed based on fuzzy control theory for each subsystem to make sure unstable system tracking desired trajectory. Finally, the computer simulator shows the effectiveness of proposed control scheme.

2 IMPACT DYNAMIC MODEL FOR CAPTURING OPERATION

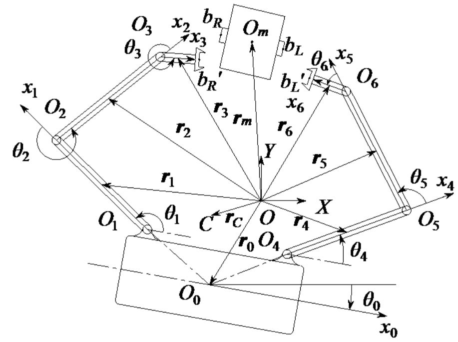

Figure.1 Structure of system in pre-impact phase

The planar dual-arm space robot and target system are 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 kinematics of the two manipulators of space can be derived as follow:

$$\boldsymbol{s}_b = \boldsymbol{J}\dot{\boldsymbol{q}} \tag{1}$$

where $\boldsymbol{s}_b = [\dot{x}_{bL} \quad \dot{y}_{bL} \quad \dot{\theta}_{bL} \quad \dot{x}_{bR} \quad \dot{y}_{bR} \quad \dot{\theta}_{bR}]^\mathrm{T}$, $\boldsymbol{J}$ is consist of $\boldsymbol{J}_L$ 、 $\boldsymbol{J}_R$. $\boldsymbol{J}_L$ 、 $\boldsymbol{J}_R$ are Jacobian matrixes.

The kinematics of the target can be derived as follow:

$$\boldsymbol{s}_{b'} = \boldsymbol{J}_m\dot{\boldsymbol{q}}_m \tag{2}$$

where $\boldsymbol{s}_{b'} = [\dot{x}_{b'L} \quad \dot{y}_{b'L} \quad \dot{\theta}_{b'L} \quad \dot{x}_{b'R} \quad \dot{y}_{b'R} \quad \dot{\theta}_{b'R}]^\mathrm{T}$ denote $\boldsymbol{J}_m = [\boldsymbol{J}_{mL}^\mathrm{T} \quad \boldsymbol{J}_{mR}^\mathrm{T}]^\mathrm{T}$, $\boldsymbol{J}_{mL}$ 、 $\boldsymbol{J}_{mR}$ are Jacobian matrixes.

The dynamic equations of the dual-arm space robot is obtained by applying the Lagrangain formulation

$$\boldsymbol{D}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{H}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} = \begin{bmatrix} \boldsymbol{0}_{2\times1} \\ \boldsymbol{\tau} \end{bmatrix} + \boldsymbol{J}^\mathrm{T}\boldsymbol{F} \tag{3}$$

where $\boldsymbol{D}(\boldsymbol{q}) \in \boldsymbol{R}^{9\times9}$ is the inertial matrix, $\boldsymbol{H}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} \in \boldsymbol{R}^{9\times1}$ is contains the corillis and centrifugal force. $\boldsymbol{\tau} = [0 \quad 0 \quad \tau_0 \quad \boldsymbol{\tau}_L^\mathrm{T} \quad \boldsymbol{\tau}_R^\mathrm{T}]^\mathrm{T}$ is the generalized control torque, $\boldsymbol{F} \in \boldsymbol{R}^{6\times1}$ is the impact force acts on the manipulators.

The dynamic equations of the target can be derived base on the Newton-Euler formulation:

$$\boldsymbol{D}_m\ddot{\boldsymbol{q}}_m = \boldsymbol{J}_m^\mathrm{T}\boldsymbol{F}' \tag{4}$$

$\boldsymbol{D}_m \in \boldsymbol{R}^{3\times3}$ is the inertial matrix, $\boldsymbol{F}'$ is counter-acting forces. According to Newton's third law

$$\boldsymbol{F}' = -\boldsymbol{F} \tag{5}$$

Impact forces can be decomposed as follow:

$$\boldsymbol{F}' = (\boldsymbol{J}_\mathrm{m}^\mathrm{T})^+\boldsymbol{M}_\mathrm{m}\ddot{\boldsymbol{q}}_\mathrm{m} + \boldsymbol{F}_I \tag{6}$$

where $(\boldsymbol{J}_\mathrm{m}^\mathrm{T})^+\boldsymbol{M}_\mathrm{m}\ddot{\boldsymbol{q}}_\mathrm{m}$ is operating force item. $\boldsymbol{F}_I$ is tensile force or pressure, and $\boldsymbol{J}_\mathrm{m}^\mathrm{T}\boldsymbol{F}_I = 0$.

With Eq.(3), Eq.(4), Eq.(5), Eq.(6), we have：

$$\begin{aligned} &\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{H}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} \\ &= \begin{bmatrix} \boldsymbol{0}_{2\times1} \\ \boldsymbol{\tau} \end{bmatrix} - \boldsymbol{J}^\mathrm{T}(\boldsymbol{J}_\mathrm{m}^\mathrm{T})^+\boldsymbol{M}_\mathrm{m}\ddot{\boldsymbol{q}}_\mathrm{m} - \boldsymbol{J}^\mathrm{T}\boldsymbol{F}_I \end{aligned} \tag{7}$$

According to theorem of impulse and ignoring $\boldsymbol{F}_I$ [9], integrating Eq.(7), after arrange, we have:

$$\begin{aligned} &\boldsymbol{M}\left[\dot{\boldsymbol{q}}(t_0+\Delta t) - \dot{\boldsymbol{q}}(t_0)\right] + \\ &\boldsymbol{J}^\mathrm{T}\left[(\boldsymbol{J}_\mathrm{m}^\mathrm{T})^{-1}\boldsymbol{M}_\mathrm{m}(\dot{\boldsymbol{q}}_\mathrm{m}(t_0+\Delta t) - \dot{\boldsymbol{q}}_\mathrm{m}(t_0))\right] = 0 \end{aligned} \tag{8}$$

Denote $\boldsymbol{q}_\mathrm{f} = [x_0 \quad y_0 \quad \theta_0 \quad \boldsymbol{\theta}_\mathrm{L}^\mathrm{T}]^\mathrm{T}$, consider the relationship of left arm and target, we have:

$$\boldsymbol{J}_\mathrm{L}\dot{\boldsymbol{q}}_\mathrm{f}(t) = \boldsymbol{J}_\mathrm{lL}\dot{\boldsymbol{q}}_\mathrm{m}(t) \tag{9}$$

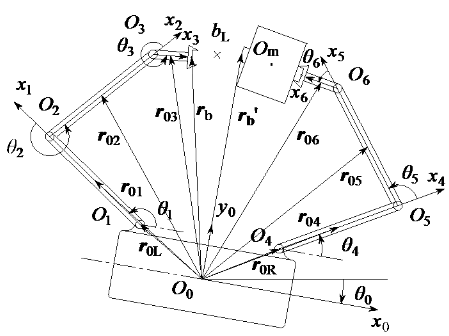

Fig.2 Dual-arm space robot with closed chain after the capture

At the cutting point b_L , we have the relationship in base-fix coordinate:

$$\boldsymbol{G}_\mathrm{L}\dot{\boldsymbol{\theta}}_\mathrm{L} = \boldsymbol{G}_\mathrm{R}\dot{\boldsymbol{\theta}}_\mathrm{R} \tag{10}$$

Let：

$$\boldsymbol{U} = [\boldsymbol{I}_{6\times6} \quad \boldsymbol{U}_1^\mathrm{T}] \tag{11}$$

$$\boldsymbol{U}_1 = [\boldsymbol{O}_{3\times3} \quad \boldsymbol{G}_\mathrm{R}^{-1}\boldsymbol{G}_\mathrm{L}] \tag{12}$$

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

With the Eq.(11), Eq. (13), Eq.(14) we have:

$$\dot{\boldsymbol{q}} = \boldsymbol{U}^\mathrm{T}\dot{\boldsymbol{q}}_\mathrm{f} \tag{13}$$

Solving Eq.(8), the velocity of system is obtained

$$\dot{\boldsymbol{q}}_{\mathrm{f}}(t_0+\Delta t)=\boldsymbol{L}^{-1}\left[\boldsymbol{R}\dot{\boldsymbol{q}}_{\mathrm{f}}(t_0)+\boldsymbol{U}\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}_{\mathrm{m}}^{\mathrm{T}})^{+}\boldsymbol{M}_{\mathrm{m}}\dot{\boldsymbol{q}}_{\mathrm{m}}(t_0)\right] \quad (14)$$

where $\boldsymbol{L}=\boldsymbol{R}+\boldsymbol{U}\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{J}_{\mathrm{m}}^{\mathrm{T}})^{+}\boldsymbol{M}_{\mathrm{m}}\boldsymbol{J}_{\mathrm{lL}}^{-1}\boldsymbol{J}_{\mathrm{L}}$, $\boldsymbol{R}=\boldsymbol{U}\boldsymbol{M}\boldsymbol{U}^{\mathrm{T}}$.

Differentiating Eq.(13)：

$$\ddot{\boldsymbol{q}}=\boldsymbol{U}^{\mathrm{T}}\ddot{\boldsymbol{q}}_{\mathrm{f}}+\dot{\boldsymbol{U}}^{\mathrm{T}}\dot{\boldsymbol{q}}_{\mathrm{f}} \quad (15)$$

Substituting Eq.(9), Eq.(13), Eq.(15) into Eq.(7) we can get:

$$\bar{\boldsymbol{M}}\ddot{\boldsymbol{q}}_{\mathrm{f}}+\bar{\boldsymbol{H}}\dot{\boldsymbol{q}}_{\mathrm{f}}=\boldsymbol{U}\begin{bmatrix}0_{2\times1}\\ \boldsymbol{\tau}\end{bmatrix}-\boldsymbol{U}\boldsymbol{J}^{\mathrm{T}}\boldsymbol{F}_I \quad (16)$$

Let

$$\bar{\boldsymbol{\tau}}=\boldsymbol{U}\begin{bmatrix}0_{2\times1}\\ \boldsymbol{\tau}\end{bmatrix},\quad \bar{\boldsymbol{F}}_I=\boldsymbol{U}\boldsymbol{J}^{\mathrm{T}}\boldsymbol{F}_I \quad (17)$$

The internal force have no influence on closed-chain system，the dynamic equation of composite as follow:

$$\bar{\boldsymbol{M}}\ddot{\boldsymbol{q}}_{\mathrm{f}}+\bar{\boldsymbol{H}}\dot{\boldsymbol{q}}_{\mathrm{f}}=\bar{\boldsymbol{\tau}} \quad (18)$$

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

$$\bar{\boldsymbol{\tau}}=\left[\bar{\boldsymbol{\tau}}_{\mathrm{a}}^{\mathrm{T}}\quad \bar{\boldsymbol{\tau}}_{\mathrm{b}}^{\mathrm{T}}\right]^{\mathrm{T}} \quad (19)$$

$$[0\quad 0\quad \boldsymbol{\tau}^{\mathrm{T}}]^{\mathrm{T}}=\left[\boldsymbol{\tau}_{\mathrm{c}}^{\mathrm{T}}\quad \boldsymbol{\tau}_{\mathrm{L}}^{\mathrm{T}}\quad \boldsymbol{\tau}_{\mathrm{R}}^{\mathrm{T}}\right]^{\mathrm{T}} \quad (20)$$

where $\boldsymbol{\tau}_{\mathrm{c}}\in\boldsymbol{R}^{3\times1}$, $\bar{\boldsymbol{\tau}}_{\mathrm{a}}$、$\bar{\boldsymbol{\tau}}_{\mathrm{b}}\in\boldsymbol{R}^{3\times1}$。

Substituting Eq.(13) into Eq.(20), we have

$$\bar{\boldsymbol{\tau}}_{\mathrm{a}}=\boldsymbol{\tau}_{\mathrm{c}}=\left[0\quad 0\quad \tau_3\right]^{\mathrm{T}}(21)\,\boldsymbol{\Omega}\left[\tau_{\mathrm{L}}^{\mathrm{T}}\quad \tau_{\mathrm{R}}^{\mathrm{T}}\right]^{\mathrm{T}}=\bar{\tau}_{\mathrm{b}} \quad (21)$$

Where $\boldsymbol{\Omega}=[\boldsymbol{I}_{3\times3}\quad \left(\boldsymbol{G}_{\mathrm{R}}^{-1}\boldsymbol{G}_{\mathrm{L}}\right)^{\mathrm{T}}]$。

3 DECENTRALIZED ADAPTIVE FUZZY CONTROL FOR CLOSED-CHAIN SYSTEM

Denote the state vectors $\boldsymbol{x}_1=[x_0\quad \dot{x}_0]^{\mathrm{T}}$，$\boldsymbol{x}_2=[y_0\quad \dot{y}_0]^{\mathrm{T}}$，$\boldsymbol{x}_3=[\theta_0\quad \dot{\theta}_0]^{\mathrm{T}}$，$\boldsymbol{x}_4=[\theta_1\quad \dot{\theta}_1]^{\mathrm{T}}$，$\boldsymbol{x}_5=[\theta_2\quad \dot{\theta}_2]^{\mathrm{T}}$，$\boldsymbol{x}_6=[\theta_3\quad \dot{\theta}_3]^{\mathrm{T}}$，the Eq.(21) can be rewritten as follow:

$$\dot{\boldsymbol{x}}_i=\boldsymbol{A}_i\boldsymbol{x}_i-\boldsymbol{B}_i s_i+\boldsymbol{E}_i\bar{\tau}_i \quad (22)$$

where $\boldsymbol{A}_i=\begin{bmatrix}0&1\\0&0\end{bmatrix}$，$\boldsymbol{B}_i=\begin{bmatrix}0\\1\end{bmatrix}$，$\boldsymbol{E}_i=\begin{bmatrix}0\\1\end{bmatrix}$，$\bar{\tau}_i$ is the ith element of $\bar{\tau}$，s_i is the ith row of $\boldsymbol{f}$:

$$\boldsymbol{f}=\hat{\bar{\boldsymbol{M}}}^{-1}(\boldsymbol{\theta})\hat{\bar{\boldsymbol{N}}}(\boldsymbol{\theta},\dot{\boldsymbol{\theta}})\dot{\boldsymbol{\theta}}+[\boldsymbol{I}-\hat{\bar{\boldsymbol{M}}}^{-1}]\bar{\boldsymbol{\tau}}\ .$$

Defining position error and velocity error as follow:

$$\begin{cases}e_i=q_{i\mathrm{d}}-q_i\\ \dot{e}_i=\dot{q}_{i\mathrm{d}}-\dot{q}_i\end{cases}\quad i=(1,2,\ldots,6) \quad (23)$$

where q_i is is the ith element of $\boldsymbol{q}_{\mathrm{f}}$, $q_{i\mathrm{d}}$ is desired trajectory.

The position of base is uncontrolled and the attitude is controlled, we have:

$$\tau_j=0\,,\quad j=(1,2)$$

The controller is designed as follow:

$$\bar{\tau}_i=u_{\mathrm{d}i}+u_{\mathrm{f}i}-u_{\mathrm{h}i} \quad (24)$$

where $u_{\mathrm{d}i}$ make the subsystem towards stability. $u_{\mathrm{f}i}$ is fuzzy control item. $u_{\mathrm{h}i}$ is robust control term.

$$u_{\mathrm{d}i}=\ddot{q}_{\mathrm{d}i}+\boldsymbol{K}_i\boldsymbol{e}_i \quad (25)$$

where $\boldsymbol{K}_i=[k_{i1}\quad k_{i2}]$.

Fuzzy control item is design as follow

$$u_{\mathrm{f}i}=\boldsymbol{W}_i^{\mathrm{T}}\boldsymbol{\xi}_i(\boldsymbol{y}_i) \quad (26)$$

$\boldsymbol{W}_i$ is parameter matrix. $\boldsymbol{W}_i^*$ is optimal matrix

To construct the fuzzy basis function

$$\xi_{ik}(y_{i1},\ldots,y_{i5})=\frac{\prod_{j=1}^{5}\mu_{iR_j^k}(y_{ij})}{\sum_{k=1}^{N}[\prod_{j=1}^{5}\mu_{iR_j^k}(y_{ij})]} \quad (27)$$

Fuzzy basis function can be expressed as $\boldsymbol{\xi}_i(\boldsymbol{y}_i)=[\xi_{i1},\ldots,\xi_{i5}]^{\mathrm{T}}$. $n=5$, the unknown nonlinear part can be regard as external disturbance and related to $\boldsymbol{y}_i=[q_i\quad \dot{q}_i\quad q_{i\mathrm{d}}\quad \dot{q}_{i\mathrm{d}}\quad \ddot{q}_{i\mathrm{d}}]$.

Poduct inference engine, singleton fuzzifier and center average defuzzifier are used to calculate outputs[10]. Choosing Gauss function as membership function $\mu_{iR_j^k}(\bullet)$, a_{ij} and b_{ij} are center and length jth word set.

$$\mu_{iR_j^k}=e^{-[(y_{ij}-a_{ijk}^2)/b_{ijk}^2]}\ (j=1,2,...,5;k=1,2,3) \quad (28)$$

Defining minimum approximation error

$$\omega_i=u_{\mathrm{f}i}(\boldsymbol{y}_i\,|\,\boldsymbol{W}_i^*)-f_i \quad (29)$$

Robust control term：

$$u_{\mathrm{h}i}=-\lambda^{-1}\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{e}_i \quad (30)$$

$\boldsymbol{P}_i$ is the solution of Ricatti equation:

$$\boldsymbol{P}_i\boldsymbol{A}_{ki}+\boldsymbol{A}_{ki}^{\mathrm{T}}\boldsymbol{P}_i-(\frac{2}{\lambda}-\frac{1}{\rho^2})\boldsymbol{P}_i\boldsymbol{B}_i\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}_i=-\boldsymbol{Q}_i \tag{31}$$

where $\boldsymbol{A}_{ki}=\begin{bmatrix}0 & 1\\ -k_{i1} & -k_{i2}\end{bmatrix}$, $\lambda>0$.

Choosing Adaptive adjustment rate of parameter matrix

$$\dot{\boldsymbol{W}}_i=-\eta\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{B}_i\xi_i(\boldsymbol{y}_i) \tag{32}$$

Weights approximation error can be written as:

$$\tilde{\boldsymbol{W}}_i=\boldsymbol{W}_i^*-\boldsymbol{W}_i \tag{33}$$

With Eq.(22), Eq. (24) we can get the error equation of system：

$$\dot{\boldsymbol{e}}_i=\boldsymbol{A}_{ki}\boldsymbol{e}_i+\boldsymbol{B}_iu_{hi}-\boldsymbol{B}_i\tilde{\boldsymbol{W}}_i^{\mathrm{T}}\boldsymbol{\xi}-\boldsymbol{B}_i\omega_i \tag{34}$$

Defining a Lyapunov function as follow:

$$V_i=\frac{1}{2}\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{e}_i+\frac{1}{2\eta}\tilde{\boldsymbol{W}}_i^{\mathrm{T}}\tilde{\boldsymbol{W}}_i \tag{35}$$

Differentiating Eq.(35), we have:

$$\begin{aligned}V_i&=\frac{1}{2}\dot{\boldsymbol{e}}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{e}_i+\frac{1}{2}\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}\dot{\boldsymbol{e}}_i+\frac{1}{\eta}\tilde{\boldsymbol{W}}_i^{\mathrm{T}}\dot{\tilde{\boldsymbol{W}}}_i\\
&=\frac{1}{2}[\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{A}_{ki}^{\mathrm{T}}\boldsymbol{P}\boldsymbol{e}_i+\boldsymbol{u}_{hi}^{\mathrm{T}}\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{e}_i-\tilde{\boldsymbol{W}}_i^{\mathrm{T}}\xi_i\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{e}_i+\omega_i\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{e}_i\\
&+\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{A}_{ki}^{\mathrm{T}}\boldsymbol{e}_i+\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{B}_i\boldsymbol{u}_{hi}-\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{B}_i\tilde{\boldsymbol{W}}_i^{\mathrm{T}}\xi_i+\omega_i\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{B}_i]+\frac{1}{\eta}\tilde{\boldsymbol{W}}_i^{\mathrm{T}}\dot{\tilde{\boldsymbol{W}}}_i\\
&=-\frac{1}{2\rho^2}\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{B}_i\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{e}_i+\frac{1}{2}\omega_i[\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{B}_i+\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{e}]-\frac{1}{2}\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{Q}_i\boldsymbol{e}_i\\
&=-\frac{1}{2}(\frac{1}{\rho}\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}_i\boldsymbol{e}-\rho\omega_i)^{\mathrm{T}}(\frac{1}{\rho}\boldsymbol{B}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{e}-\rho\omega_i)\\
&\quad-\frac{1}{2}\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{Q}_i\boldsymbol{e}_i+\frac{1}{2}\rho^2\omega_i^2\le-\frac{1}{2}\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{Q}_i\boldsymbol{e}_i+\frac{1}{2}\rho^2\omega_i^2\end{aligned} \tag{36}$$

Integrating Eq.(36) from 0 to T

$$V_i(T)-V_i(0)\le\int_0^{\mathrm{T}}(-\frac{1}{2}\boldsymbol{e}_i^{\mathrm{T}}\boldsymbol{Q}_i\boldsymbol{e}_i+\frac{1}{2}\rho^2\omega_i^2) \tag{37}$$

Since $V_i(T)\ge0$, and comprehensive each subsystem we have:

$$\frac{1}{2}\int_0^{\mathrm{T}}\boldsymbol{e}^{\mathrm{T}}\boldsymbol{Q}\boldsymbol{e}\le\boldsymbol{e}^{\mathrm{T}}(0)\boldsymbol{P}\boldsymbol{e}(0)+\frac{1}{\eta}\tilde{\boldsymbol{W}}^{\mathrm{T}}(0)\tilde{\boldsymbol{W}}(0)+\rho^2\boldsymbol{\omega}^{\mathrm{T}}\boldsymbol{\omega} \tag{38}$$

$\bar{\boldsymbol{\tau}}$ is reduced order, the actual force/torques $\boldsymbol{\tau}$ is obtained by the weighted minimum-norm solution.

$$\begin{bmatrix}\boldsymbol{\tau}_L\\ \boldsymbol{\tau}_R\end{bmatrix}=\boldsymbol{Z}\boldsymbol{\Omega}^{\mathrm{T}}\left(\boldsymbol{\Omega}\boldsymbol{Z}\boldsymbol{\Omega}^{\mathrm{T}}\right)^{-1}\bar{\boldsymbol{\tau}}_{\mathrm{b}} \tag{39}$$

Where $\boldsymbol{Z}\in\boldsymbol{R}^{6x6}$ is symmetric positive definite matrix.

4 SIMULATION RESULTS

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 $d_0=1.062\mathrm{m}$, $d_{\mathrm{L}}=0.5\mathrm{m}$, $d_{\mathrm{R}}=0.5\mathrm{m}$, $l_i=2\mathrm{m}$ $(i=1,2,4,5)$, $l_j=0.5\mathrm{m}$ $(\mathrm{j}=3,6)$, $m_0=200\mathrm{kg}$, $m_{\mathrm{m}}=50\mathrm{kg}$, $m_i=20\mathrm{kg}$ $(i=1,2,4,5)$, $m_j=5\mathrm{kg}$ $(j=3,6)$, $I_0=50\mathrm{kg\cdot m^2}$, $I_{\mathrm{m}}=10\mathrm{kg\cdot m^2}$, $I_i=10\mathrm{kg\cdot m^2}$ $(i=1,2,4,5)$, $I_j=2\mathrm{kg\cdot m^2}$ $(j=3,6)$.

The initial state of base and load is:

$$\boldsymbol{q}=[0.3\mathrm{m}\ \ 0.3\mathrm{m}\ \ 0^\circ\ \ 120^\circ-60^\circ\ \ -60^\circ\ \ 60^\circ\ 60^\circ\ \ 60^\circ]^{\mathrm{T}}$$

If we know the joint angles of left arm $\boldsymbol{\theta}_{\mathrm{L}}$, the joint angles of right $\boldsymbol{\theta}_{\mathrm{R}}$ can be calculate by angle solver as follow:

$$\theta_4=\pi+\theta_1+\theta_2+\theta_3-\theta_5-\theta_6$$

$$\begin{aligned}\theta_5=\pi-&\mathrm{ac}\{l_5^2+l_4^2-l_{36}^2-l_{14}^2-l_{13}^2+2l_{14}l_{13}\mathrm{c}\{\theta_1-\\
&\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}-l_{36}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-\\
&2l_{14}l_{13}\mathrm{c}\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}\}\mathrm{c}\{\pi+\\
&\theta_3-\mathrm{ac}[(l_2^2+l_{13}^2-l_1^2)/2l_1l_{13}]\}/\{2l_{13}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-\\
&2l_{14}l_{13}\mathrm{c}\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}\}\}\}\}/2l_4l_5\}\end{aligned}$$

$$\begin{aligned}\theta_6=\pi-&\mathrm{ac}\{\{2l_{36}^2-2l_{36}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\mathrm{c}\{\theta_1-\\
&\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}\}\mathrm{c}\{\pi+\theta_3-\arccos[(l_2^2+\\
&l_{13}^2-l_1^2)/2l_2l_{13}]\text{-}\mathrm{ac}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\cos\{\theta_1-\\
&\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}/\{2l_{13}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-\\
&2l_{14}l_{13}\cos\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}\}\}\}\}/\\
&\{2l_{36}\mathrm{sqrt}\{l_{36}^2+l_{14}^2+l_{13}^2-2l_{14}l_{13}\cos\{\theta_1-\mathrm{ac}[(l_1^2+\\
&l_{13}^2-l_2^2)/2l_1l_{13}]\}/\{2l_{13}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\mathrm{c}\{\theta_1-\\
&\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}\text{-}2\{2l_{36}^2-2l_{36}\mathrm{sqrt}\{l_{14}^2+\\
&l_{13}^2-2l_{14}l_{13}\mathrm{c}\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}/\\
&\{2l_{13}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\cos\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-\\
&l_2^2)/2l_1l_{13}]\}\}\}\}\}\}\}\}-\mathrm{ac}\{\{l_5^2-l_{36}^2+l_{14}^2+l_{13}^2-\\
&2l_{14}l_{13}\mathrm{c}\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}-\\
&2l_{36}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\mathrm{c}\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-\\
&l_2^2)/2l_1l_{13}]\}\mathrm{c}\{\pi+\theta_3-\arccos[(l_2^2+l_{13}^2-l_1^2)/\\
&2l_2l_{13}]\text{-}\mathrm{ac}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\cos\{\theta_1-\mathrm{ac}[(l_1^2+\\
&l_{13}^2-l_2^2)/2l_1l_{13}]\}/\{2l_{13}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\cos\{\theta_1-\\
&\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}\}\}\}-l_{14}^2\}\{2l_{36}\mathrm{sqrt}\{l_{36}^2+\\
&l_{14}^2+l_{13}^2-2l_{14}l_{13}\cos\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}/\\
&\{2l_{13}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\mathrm{c}\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/\\
&2l_1l_{13}]\}-2\{2l_{36}^2-2l_{36}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-2l_{14}l_{13}\mathrm{c}\{\theta_1-\\
&\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}/\{2l_{13}\mathrm{sqrt}\{l_{14}^2+l_{13}^2-\\
&2l_{14}l_{13}\cos\{\theta_1-\mathrm{ac}[(l_1^2+l_{13}^2-l_2^2)/2l_1l_{13}]\}\}\}\}\}\}\}\end{aligned}$$

where， $l_{13}=\mathrm{sqrt}[l_1^2+l_2^2-2l_1l_2\mathrm{c}(\pi+\theta_2)]$， l_{14} is the distance from O_1 to O_4， $l_{36}=(l_3+d_{\mathrm{L}}+d_{\mathrm{R}}+l_6)$。 $\mathrm{c}(\cdot)$ express cosine function, $\mathrm{ac}(\cdot)$ express arc-cosine function $\mathrm{sqrt}(\cdot)$ express square root functions.

The initial velocity of the target are:

$\dot{x}_{\text{load}} = 0\text{m/s}$, $\dot{y}_{\text{load}} = 0\text{m/s}$, $\dot{\theta}_{\text{load}} = 0.35\text{rad/s}$.

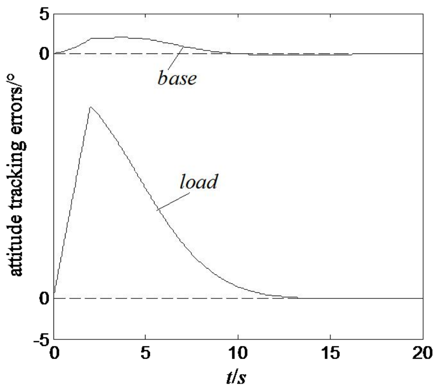

Figure.3 Attitude angle tracking errors of base and load

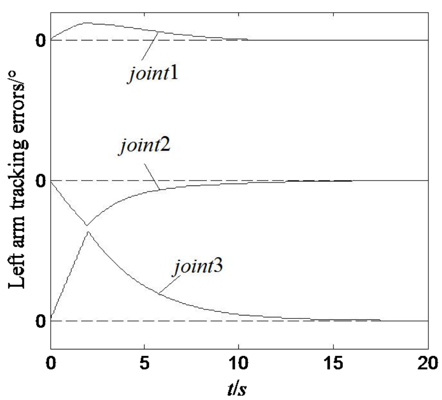

Figure.4 Joint angles tracking errors of left arm

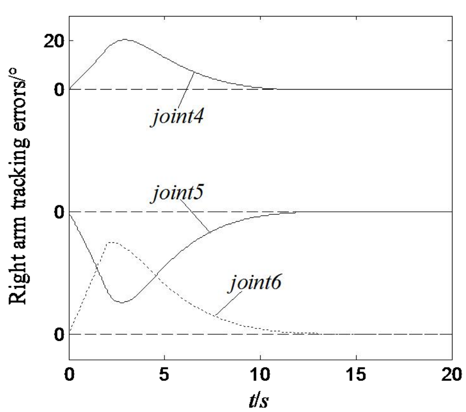

Figure.5 Joint angles tracking errors of right arm

Two seconds after the capturing operation, let the controller work. Figure3, Figure4, and Figure5 show the proposed control method calm down the disturb motion, system restore to a stable state.

5 CONCLUSION

In this paper, the impact dynamics of dual-arm space robot capturing a target is analyzed. The impact force effect is great for the composite system after the impact. The unstable system can be calmed down by proposed control scheme.

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