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 results[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] derive the impact model by extended inertia tensor concept. Yoshida et al.[9] 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 Fig. 1. 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 \( x_iO_y(i=1,2,\cdots,6) \). \( O_b \), \( O_m \) 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 \( O_6 \ O_1 \) and \( O_6 \ O_2 \) are \( d_b \). The distance of mass center of load \( O_m \) to end-effector are \( d_1 \) and \( d_2 \).

The kinematics of the two manipulators of space can be derived as follow:

\[
s_b = J\dot{q}
\]

(1)

where \( s_b = [\dot{x}_{bl} \ y_{bl} \ \dot{\theta}_{bl} \ \dot{\theta}_{br}]^T \), \( J \) is consist of \( J_l \ , \ J_b \ , \ J_l \ , \ J_b \) are Jacobian matrixes.

The kinematics of the target can be derived as follow:

\[
s_u = J_u\dot{q}_u
\]

(2)

where \( s_u = [\dot{x}_{uL} \ y_{uL} \ \dot{\theta}_{uL} \ \dot{\theta}_{uR}]^T \), \( J_u \) denotes \( [J_{ul} \ J_{ur}] \), \( J_{ul} \ , \ J_{ur} \) are Jacobian matrixes.

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

\[
\mathbf{D}(\dot{q})\ddot{q} + \mathbf{H}(q,\dot{q})\dot{\theta} = \begin{bmatrix} \theta_{s\dot{z}1} \\ \theta_{r\dot{\theta}} \end{bmatrix} + J^tF
\]

(3)

where \( \mathbf{D}(\dot{q}) \in \mathbb{R}^{6\times6} \) is the inertial matrix, \( \mathbf{H}(q,\dot{q})\dot{\theta} \in \mathbb{R}^{6\times1} \) contains the corollis and centrifugal force. \( \tau = [0 \ 0 \ r_0 \ \tau_1^x \ \tau_2^y \ r_3^x] \) is the generalized control torque, \( F \in \mathbb{R}^{6\times1} \) is the impact force acts on the manipulators.

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

\[
\mathbf{D}_u\ddot{q}_u = J_{u}^tF'
\]

(4)

\( \mathbf{D}_u \in \mathbb{R}^{3\times3} \) is the inertial matrix, \( F' \) is counter-acting forces. According to Newton's third law

\[
F' = -F
\]

(5)

Impact forces can be decomposed as follow:

\[
F' = (J_{m}^t)^\prime \mathbf{M}_u\ddot{q}_m + F_i
\]

(6)

where \( (J_{m}^t)^\prime \mathbf{M}_u\ddot{q}_m \) is operating force item. \( F_i \) is tensile force or pressure, and \( J_{m}^tF_i = 0 \).

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

\[
\mathbf{M}(q)\ddot{q} + \mathbf{H}(q,\dot{q})\dot{\theta} = \begin{bmatrix} \theta_{s\dot{z}1} \\ \tau \end{bmatrix} - J^t(J_{m}^t)^\prime \mathbf{M}_u\ddot{q}_m - J^tF_i
\]

(7)

According to theorem of impulse and ignoring \( F_i \), integrating Eq.(7), after arrange, we have:

\[
\mathbf{M}[\ddot{q}(t_0 + \Delta t) - \ddot{q}(t_0)] + J^t[(J_{m}^t)^\prime \mathbf{M}_u(\ddot{q}(t_0 + \Delta t) - \ddot{q}(t_0))] = 0
\]

(8)

Denote \( \dot{q}_i = [x_0 \ y_0 \ \dot{\theta}_0 \ \dot{\theta}_3]^T \), consider the relationship of left arm and target, we have:

\[
J_{u}\ddot{q}_u(t) = J_{u}\ddot{q}_m(t)
\]

(9)

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

At the cutting point \( h_L \), we have the relationship in base-fix coordinate:

\[
G_L\dot{h}_L = G_0\dot{h}_K
\]

(10)

Let:

\[
U = [I_{n \times n} \ U_1^T]
\]

(11)

\[
U_1 = [O_{n \times 3} G_{R}^T G_{L}]
\]

(12)

\( I_{n \times n} \) is a \( n \times n \) unit matrix, \( O_{n \times n} \) is a \( n \times n \) zero matrix.

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

\[
\dot{q} = U^T\dot{q}_i
\]

(13)
Solving Eq.(8), the velocity of system is obtained
\[ \dot{q}(t_0 + \Delta t) = L \left[ R \dot{q}(t_0) + UJ^T (J^T M_\omega \dot{q}(t_0)) \right] \]
(14)
where \( L = R + UJ^T J^T M_\omega J^T J^T \), \( R = UMU^T \).
Differentiating Eq.(13):
\[ \ddot{q} = U^T \ddot{q}_t + U^T \ddot{q}_l \]
(15)
Substituting Eq.(9), Eq.(13), Eq.(15) into Eq.(7) we can get:
\[ \ddot{\tilde{q}} = U \left[ \begin{array}{c} 0_{2s} \end{array} \right] \tau + UJ^T F_i \]
(16)
Let
\[ \tau = U \left[ \begin{array}{c} 0_{2s} \end{array} \right] \tau, \quad \ddot{F}_i = UJ^T F_i \]
(17)
The internal force has no influence on closed-chain system, the dynamic equation of composite as follow:
\[ \ddot{\tilde{q}}_i + \ddot{\tilde{q}}_l = \tau \]
(18)
\( \tau \) and inputs can be rewritten as follow:
\[ \tau = \left[ \begin{array}{c} \tau_i \\ \tau_l \end{array} \right], \quad \ddot{F}_i = \left[ \begin{array}{c} \ddot{F}_i \\ \ddot{F}_l \end{array} \right] \]
(19)
[0 0 \tau_1^T]^T = \left[ \begin{array}{c} \tau_1 \\ \tau_2 \\ \tau_3 \end{array} \right]^T \]
(20)
where \( \tau_i \in R^{2s_1}, \tau_l \in R^{2s_2} \).
Substituting Eq.(13) into Eq.(20), we have
\[ \ddot{\tilde{q}}_i = \ddot{\tilde{q}}_l = [0 0 \tau_i]^T \Omega \left[ \begin{array}{ccc} r_1 \\ r_2 \\ r_3 \\ r_4 \end{array} \right] = \ddot{F}_i \]
(21)
Where \( \Omega = [I_{s_1} \left( G_x G_x^T \right)] \).

3 DECENTRALIZED ADAPTIVE FUZZY CONTROL FOR CLOSED-CHAIN SYSTEM

Denote the state vectors \( x_1 = [x_0, \dot{x}_0]^T, \quad x_2 = [x_0, \dot{x}_0]^T, \quad x_3 = [\theta_0, \dot{\theta}_0]^T, \quad x_4 = [\theta_0, \dot{\theta}_0]^T, \quad x_5 = [\theta_0, \dot{\theta}_0]^T, \quad x_6 = [\theta_0, \dot{\theta}_0]^T \), the Eq.(21) can be rewritten as follow:
\[ \dot{x} = A_x x + B_{\dot{x}l} + E_{lT} \]
(22)
where \( A_x = \left[ \begin{array}{cc} 0 & 1 \\ 0 & 0 \end{array} \right], \quad B_l = \left[ \begin{array}{c} 0 \\ 1 \end{array} \right], \quad E_{lT} = \left[ \begin{array}{c} 0 \\ 1 \end{array} \right], \quad \tau_i \)
the \( i \)th element of \( \tau \), \( x_i \) is the \( i \)th row of \( f \):
\[ f = \hat{M}^{-1}(\theta) \hat{N}(\theta, \dot{\theta}) \dot{\theta} + [1 - \hat{M}^{-1}] \tau \]
\[ P_iA_{ii} + A_i^TP_i - \frac{2}{\lambda} \rho^{-1}P_iPB_iB_i^TP_i = -Q_i \]  
(31)

where \( A_{ii} = \begin{bmatrix} 0 & 1 \\ -k_{ii} & -k_{ii} \end{bmatrix} \), \( \lambda > 0 \).

Choosing Adaptive adjustment rate of parameter matrix

\[ \dot{W} = -\eta e_i \hat{P}_{BB_i} \xi (y_i) \]  
(32)

Weights approximation error can be written as:

\[ \dot{W} = W^* - W \]  
(33)

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

\[ \dot{e}_i = A_i e_i + B_i u_{ai} - B W_i \hat{\xi}_i - B_i w_0 \]  
(34)

Defining a Lyapunov function as follow:

\[ V_i = \frac{1}{2} e_i^T \hat{P}_i e_i + \frac{1}{2} \eta \dot{W}_i^T \dot{W}_i \]  
(35)

Differentiating Eq.(35), we have:

\[ V_i = \frac{1}{2} e_i^T \hat{P}_i e_i + \frac{1}{2} \eta \dot{W}_i^T \dot{W}_i \]

\[ = \frac{1}{2} \left[ e_i^T A_i e_i + u_{ai}^T B_i^T \hat{P}_i e_i - \dot{W}_i^T \hat{\xi}_i B_i^T \hat{P}_i e_i + \alpha_0 B_i^T \hat{P}_i e_i \right] \]

\[ + e_i^T P_i B_i \dot{e}_i - e_i^T P_i B_i \dot{\hat{\xi}}_i + \frac{1}{2} \hat{\xi}_i^T \hat{W}_i \]  
(36)

Integrating Eq.(36) from 0 to \( T \)

\[ V_i(T) - V_i(0) \leq \int_0^T \left( -\hat{W}_i^T \dot{W}_i + \frac{1}{2} \dot{\alpha}_0^T \dot{\alpha}_0 \right) \]  
(37)

Since \( V_i(T) \geq 0 \), and comprehensive each subsystem we have:

\[ \int_0^T e_i^T \hat{P}_i e_i \leq \int_0^T e_i^T (0) P_i e_i (0) + \int_0^T \dot{W}_i^T (0) \dot{W}_i (0) + \rho \dot{\alpha}_0 \dot{\alpha}_0 \]  
(38)

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

\[ \begin{bmatrix} \tau_t \\ \tau_s \end{bmatrix} = Z \Omega^T (\Omega Z \Omega^T)^{-1} \bar{\tau} \]  
(39)

Where \( Z \in R^{n \times n} \) 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:

\( a_i = 1.062m \), \( d_i = 0.5m \), \( d_0 = 1.062m \),

\( l_i = 2m \ (i = 1, 2, 4, 5) \), \( l_0 = 5m \ (j = 3) \),

\( m_0 = 200kg \), \( m_m = 50kg \), \( m_i = 20kg \) \( (i = 1, 2, 4, 5) \),

\( m_j = 5kg \) \( (j = 3) \), \( I_0 = 50kg \cdot m^2 \), \( I_n = 10kg \cdot m^2 \),

\( I_j = 10kg \cdot m^2 \ (i = 1, 2, 4, 5) \), \( I_0 = 2kg \cdot m^2 \) \( (j = 3) \).

The initial state of base and load is:

\[ q = \begin{bmatrix} 0.3m & 0.3m & 0 & 1200 & -60 & -60 \end{bmatrix}^T \]

If we know the joint angles of left arm \( \theta_l \), the joint angles of right \( \theta_r \) can be calculate by angle solver as follow:

\[ \theta_l = \pi - \alpha \cos \left( \frac{\theta_l}{2} \right) \left( \frac{\theta_l}{2} - \frac{\theta_l}{2} \right) + 2 \theta_1 \cos (\theta_l - \alpha \cos \left( \frac{\theta_l}{2} \right) \left( \frac{\theta_l}{2} - \frac{\theta_l}{2} \right)) + c(\theta_l - \alpha \cos \left( \frac{\theta_l}{2} \right) \left( \frac{\theta_l}{2} - \frac{\theta_l}{2} \right)) + \frac{\theta_l}{2} \]

\[ \theta_r = \pi - \alpha \cos \left( \frac{\theta_r}{2} \right) \left( \frac{\theta_r}{2} - \frac{\theta_r}{2} \right) + 2 \theta_1 \cos (\theta_r - \alpha \cos \left( \frac{\theta_r}{2} \right) \left( \frac{\theta_r}{2} - \frac{\theta_r}{2} \right)) + c(\theta_r - \alpha \cos \left( \frac{\theta_r}{2} \right) \left( \frac{\theta_r}{2} - \frac{\theta_r}{2} \right)) + \frac{\theta_r}{2} \]

where, \( l_{ij} = \text{sqrt} \left( l_i^2 + l_j^2 - 2l_i l_j \cos (\theta_l + \theta_r) \right) \), \( l_{14} \) is the distance from \( Q_i \) to \( O_i \), \( l_{1j} \) is defined as \( c(\cdot) \) express cosine function, \( ac(\cdot) \) express arccosine function \( \text{sqrt}(\cdot) \) express square root functions.
The initial velocity of the target are:
\[
\begin{align*}
\dot{x}_{\text{load}} &= 0 \text{m/s}, \quad \dot{y}_{\text{load}} = 0 \text{m/s}, \quad \dot{\theta}_{\text{load}} = 0.35 \text{rad/s}.
\end{align*}
\]

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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References


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