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 $H_\infty$ 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 focus 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 $H_\infty$ 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 $x_iOy_i$ $(i = 1, 2, \cdots, 6)$. $O_b \cdots O_9$ 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 $O_b$ and $O_i$. $l_i$ $(i = 1, 2, \cdots, 6)$ is the length of $O_b O_i$ and $O_9 O_i$ are $d_l$ and $d_g$. The distance of mass center of load $O_m$ to end-effector are $d_l$ and $d_g$. The dual-arm space robot forms a closed-chain after the capture operation.

\[ \theta = \begin{bmatrix} \theta_1 & \theta_2 & \theta_3 \end{bmatrix} \]

$\tau$ is the generalized control torque. For the convenience of description, system dynamic equations is rewritten as:

\[ M\ddot{q} + H\dot{q} = \tau \]

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

\[ x^T(M - 2H)x = 0 \]

$M - 2H$ 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 $O_i$ are given as:

\[ \begin{align*} 
    r_{bi} &= (x_{bi}, y_{bi}) \\
    r_{bi} &= r_{bi} + l_i e_{a1} + l_i e_{a2} + (d_l + d_g) e_{a3} \\
    r_{bi} &= (x_{bi}, y_{bi}) \\
    r_{bi} &= r_{bi} + l_i e_{a1} + l_i e_{a2} + d_g e_{a3} \\
    r_{bi} &= (x_{bi}, y_{bi}) \\
    r_{bi} &= (x_{bi}, y_{bi}) \\
\end{align*} \]

$\mathbf{r}_{bi}$ and $\mathbf{r}_{ai}$ are position vectors from $O_i$ and $O_a$ to $O_b$ in base-fix coordinate, $e_{ai}$ is base vector.

Depending on the characters of motion reference points, thus

\[ N_i \dot{\theta}_l = N_i \dot{\theta}_r \]

Let

\[ U = [I_{6 \times 6}, \mathbf{U}_1^T] \]

\[ U = [I_{6 \times 6}, \mathbf{U}_1^T] \]
\[ U_i = [O_{i\times n} \quad N_{i}^T N_{i}] \]  
(8)

\[ I_{n \times n} \text{ is a } n \times n \text{ unit matrix, } O_{n \times n} \text{ is a } n \times n \text{ zero matrix.} \]

The generalized coordinates matrix of closed-chain system is defined as:
\[ q_i = [x_0 \quad y_0 \quad \theta_0 \quad \theta_i] \]  
(9)

According to Eq.(9), Eq. (10), Eq. (11) and Eq. (12), can get:
\[ \dot{q} = Uq, \]  
(10)

Differentiating Eq. (10), we have
\[ \ddot{q} = U^T \ddot{q} + \dot{U}^T \dot{q}, \]  
(11)

Substituting Eq.(10), Eq.(11) into Eq.(3), the dynamic equations of closed-chain are obtained as follow:
\[ \ddot{q} = \ddot{q} + \ddot{q}, \]  
(12)

where
\[ \ddot{q} = \ddot{q} + \ddot{q}, \]  
(13)

\[ \ddot{q} = \ddot{q} + \ddot{q}, \]  
(14)

\[ \ddot{q} = \ddot{q} + \ddot{q}, \]  
(15)

In the dynamic equations of closed-chain system, For arbitrary \( y \in \mathbb{R}^{n \times 1}, \ddot{q} \in \mathbb{R}^{n \times 1}, \ddot{q} \in \mathbb{R}^{n \times 1} \) still satisfy that:
\[ y^T (\dddot{q} - 2 \dddot{q}) y = 0 \]  
(16)

\[ \dddot{q} - 2 \dddot{q} \] is skew symmetric.

So far, we have obtained 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 Fig.2.

Input layer
\[ \text{Input} = [\text{Input}]^{(1)} = [x_i] (i = 1, 2, ..., m) \]  
(17)

Superscript means which layer the input and output belong to.

Member function layer:
\[ \text{Member} = [\text{Member}]^{(1)} = \mu(\text{Input})^{(1)} = e^{-\frac{\|\text{Input} - \text{Center}\|}{\text{Width}}} \]  
(18)

### Fuzzy reasoning layer:
\[ \text{Output}^{(3)} = \prod_{k=1}^{l} w_{i,k} \text{Input}^{(3)} (k = 1, 2, ..., l) \]  
(19)

![Figure 3: Structure of recurrent fuzzy neural network](image)

Output layer, the layer of defuzzification:
\[ y_r = \text{Output}^{(4)} = w_{i,r} \text{Input}^{(4)} (r = 1, 2, ..., s) \]  
(20)

Output can be written as follow:
\[ u = W^T \Phi \]  
(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:
\[ X = [x_0 \quad y_0 \quad \theta_0 \quad x_m \quad y_m \quad \theta_m]^T \]  
(22)

Differentiating the Eq.(22):
\[ \dot{X} = J_s(q_i) \dot{q}_i \]  
(23)

\( J_s(q_i) \in \mathbb{R}^{n \times n} \) is the Jacobian matrix.

Defining the output error as follow:
\[ e = X - \tilde{X} \]  
(24)

With Eq.(24), the dynamic equations of closed-chain system can be rewritten as:
\[ M \ddot{X} + H \dot{X} = \dddot{X} \]  
(25)

Where \( M \in \mathbb{R}^{n \times n}, H \in \mathbb{R}^{n \times n} \) is the Jacobian matrix.

Since the uncertain parameters of system, we can get:
\[ \tilde{M} \ddot{X} + \tilde{H} \dot{X} + f(\delta) = \dddot{X} \]  
(26)

Where \( \tilde{M} \), \( \tilde{H} \) is nominal model, \( \Delta M \), \( \Delta H \) is model error, and \( f(\delta) = M(\Delta \dot{X} + \Delta H \dot{X}) \) is model error.

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

$$f(\delta) = W^T \Phi + \Delta \delta$$  \hspace{1cm} (27)$$

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

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

$$\tau = \dot{M}_x(\dot{X}_d + K_1 \dot{e} + K_2 e) + \dot{H}_x \dot{X} + W^T \Phi + \mu$$  \hspace{1cm} (28)$$

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

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

$$\dot{M}_x(\dot{e} + K_1 \dot{e} + K_2 e) - \dot{W}^T \Phi - \Delta \delta + \mu = 0$$  \hspace{1cm} (29)$$

where $\dot{W} = W^* - W$.

Denote $Y = [y_1^T, y_2^T] = [e^T, \dot{e}^T]^T$, we have:

$$\begin{bmatrix}
\dot{y}_1 \\
\dot{y}_2
\end{bmatrix} =
\begin{bmatrix}
0 & I_{6 \times 6} \\
-K_y & -K_y
\end{bmatrix}
\begin{bmatrix}
y_1 \\
y_2
\end{bmatrix} -
\begin{bmatrix}
-K_y & -K_y, y_1 + (\dot{e} + K_1 \dot{e} + K_2 e)
\end{bmatrix}$$  \hspace{1cm} (30)$$

The state space equations can be written as:

$$\dot{Y} = AY + B\dot{M}_x(\dot{W}^T \Phi + \Delta \delta - \mu)$$  \hspace{1cm} (31)$$

where $A = \begin{bmatrix} 0 & I_{6 \times 6} \\ -K_y & -K_y \end{bmatrix}, B = \begin{bmatrix} 0_{6 \times 6} \\ I_{6 \times 6} \end{bmatrix}$, The approximation errors of the system can be regard as external disturbance, and $z = \dot{M}_x(\Delta \delta \in L_2[0, \infty)$. There is a positive constant $O_\delta$ let $\int_0^t \|\dot{M}_x(\Delta \delta\|^2 dt \leq O_\delta$.

Robust item is designed as follow:

$$\mu = \dot{M}_x R^T B^T P y$$  \hspace{1cm} (32)$$

$R = R^T$ is gain matrix, positive definite matrix $P$ satisfy the Riccati equation:

$$PA + A^T P + PB(I - \frac{1}{\omega^2} I_{6 \times 3} - 2 R^T)B^T P = -Q$$  \hspace{1cm} (33)$$

where $\omega$ is disturbance attenuation index $Q$ is positive definite matrix

Choosing the weights of the adaptive law as follow:

$$\dot{W} = A^T \Phi y^T PB \dot{M}_x$$  \hspace{1cm} (34)$$

To verify the stability and $H_\infty$ tracking characteristics of the system, the Lyapunov function is defined as follow:

$$V = \frac{1}{2} y^T P y + \frac{1}{2} \text{tr}(\dot{W}^T A \dot{W})$$  \hspace{1cm} (35)$$

Differentiating Eq.(35)

$$\dot{V} = \frac{1}{2} y^T P y + \frac{1}{2} y^T \dot{P} y + \frac{1}{2} \text{tr}(\dot{W}^T A \dot{W}) + \frac{1}{2} \text{tr}(A \dot{W}^T A \dot{W})$$

$$= \frac{1}{2} \left[ Ay + B \dot{M}_x(\dot{W}^T \Phi + \Delta \delta - \mu) \right]^T P y + \frac{1}{2} y^T P \left[ Ay + B \dot{M}_x(\dot{W}^T \Phi + \Delta \delta - \mu) \right] + \frac{1}{2} \text{tr}(\dot{W}^T A \dot{W})$$

$$= \frac{1}{2} y^T (PA + A^T P + PB(I - \frac{1}{\omega^2} I_{6 \times 3} - 2 R^T)B^T P) y - \frac{1}{2} \left( B^T P y - \omega \tilde{Z} \right)^T \left( B^T P y - \omega \tilde{Z} \right) + \frac{1}{2} \omega^2 \tilde{Z}^T \tilde{Z}$$

$$\leq \frac{1}{2} y^T Q y + \frac{1}{2} \omega^2 \tilde{Z}^T \tilde{Z}$$ \hspace{1cm} (36)$$

Integrating Eq.(36) from 0 to T :

$$V(T) - V(0) \leq \frac{1}{2} \int_0^T y^T Q y + \frac{1}{2} \omega^2 \int_0^T \tilde{Z}^T \tilde{Z} dt$$  \hspace{1cm} (37)$$

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

$$\frac{1}{2} \int_0^T y^T Q y \leq V(0) + \frac{1}{2} \omega^2 \int_0^T \tilde{Z}^T \tilde{Z} dt$$

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

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

$$\bar{r} = [\bar{r}_y, \bar{r}_\dot{y}]^T$$  \hspace{1cm} (38)$$

$$\tau = [\tau_\dot{y}, \tau_y, \tau']^T$$  \hspace{1cm} (39)$$

From the preview derivation process, we have:

$$\bar{r}_\dot{y} = \bar{r}_y$$  \hspace{1cm} (40)$$

$$\begin{bmatrix}
\bar{r}_\dot{y} \\
\tau_y \\
\tau_\dot{y}
\end{bmatrix} = E \Omega \left( \Omega E \Omega^T \right)^{-1} \bar{r}_y$$  \hspace{1cm} (41)$$

Where $E$ is gain matrix, $\Omega = [I_{3 \times 3} (N_y N_z)^T]$.

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:

$d_y = 1.062m, d_1 = 0.5m, d_2 = 0.5m, l_i = 2m (i = 1, 2, 4) , l_j = 0.5m (i = 3, 6) , m_y = 200kg, m_m = 50kg, m_l = 20kg (i = 1, 2, 4, 5) , m_j = 5kg (j = 3, 6) , I_y = 0kg \cdot m^2, I_m = 10kg \cdot m^2, I_l = 10kg \cdot m^2 (i = 1, 2, 4, 5) , I_j = 2kg \cdot m^2 (j = 3, 6)$.

The initial state of base and load is:
The desired state of base and load is:

\[ X_d = [0 \text{m} \ 0 \text{m} \ 0^\circ \ 0 \text{m} \ 3 \text{m} \ 0^\circ]^T \]

The proposed control method can be extended to multi-arm and multi-link space robot system. The control scheme dispense with accurate system model or linear parameterization of the system dynamic equations.

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**References**


