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The Space Redundant Robotic Manipulator Chaotic Motion Dynamics Control Algorithm

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Abstract: A free-floating space redundant robotic manipulator dynamics model is established and the dynamics equation is derived, the delayed feedback control time and the self-adaptive gain coefficient are obtained by substituting into delayed feedback control equations. Then simulated dynamics control chaotic motion of the space redundant robotic manipulator, the simulation results show that the chaotic motion of the space redundant robotic manipulator becomes the periodic motion by dynamics control, therefore it is effective that dynamics control as the space redundant robotic manipulator chaotic motion control. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Space, Free-floating, Redundant robotic manipulator, Dynamic control, Chaotic control.

1. Introduction

With the development of space science and technology, the human desire to explore space is more and more enhancing; space robotic manipulator can help humans to accomplish tasks such as air rescue, air repair, air refueling, air maintenance and other air tasks, so the space robotic manipulator becomes a hot research [1]. The robotic manipulator are often required to complete some tasks, such as tracking the target in any posture, in a flexible way in replacing human work, that's need to increase DOF (the degree of freedom) of the robotic manipulator to improve flexibility, and the number of DOF are more than the dimensions needed to complete the task, this additional DOF called redundant DOF, robotic manipulator with redundant DOF called redundant robotic manipulator [2-5]. Redundant robotic manipulator has greater flexibility and more accurate target tracking capability, better obstacle and singularity avoidance ability, therefore often used as intelligent robotic manipulator actuators, and become a hot research field of the mechanical engineering and automatic control [6-7].

Redundant robotic manipulator has null space or redundant space, and its null space self-motion can generate chaotic motion; the redundant robotic manipulator chaotic motion control is one of a difficulty in robotic manipulator control [8].

Matthew [9] studied the redundant robotic manipulator chaotic motion, a planar 3R redundant robotic manipulator chaotic motion in self-motion was found by the system Poincare figure and power spectrum, but didn't study the conditions generating chaotic motion and control algorithms. Li [10] studied the dual pendulum mechanism chaotic phenomena by numerical method, and obtained parameter conditions generated chaotic motion. Zhang [11] studied the planar 3R redundant robotic manipulator chaotic motion, the parameters were

selected appropriately and the chaotic motion was changed into regular periodic motion successfully by delayed feedback control method at the expense flexibility. These studies are based on ground redundant robotic manipulator, and the study that the chaotic motion control based on the free-float space redundant robotic manipulator is still relatively little, a control algorithm is proposed that can control the chaotic motion in the space free-float redundant robotic manipulator self-motion in this paper.

In this paper, the robotic manipulator dynamic equations are derived firstly under the condition that the momentum and angular momentum conservation by using of the rigid body dynamics modeling methods [12-14], then dynamic control algorithm is proposed combined with self-adaptive delayed feedback control, and finally simulated the chaotic motion control in the space free-float redundant robotic manipulator by dynamic control algorithm, the simulation results show that the dynamic control algorithm proposed in this paper is an effective in controlling the chaotic motion control in the space free-float redundant robotic manipulator.

2. The Space Redundant Robotic Manipulator Dynamics

2.1. Description of the Space Redundant Robotic Manipulator

The model of the space free-float redundant robotic manipulator with n-DOF is shown in Fig. 1.

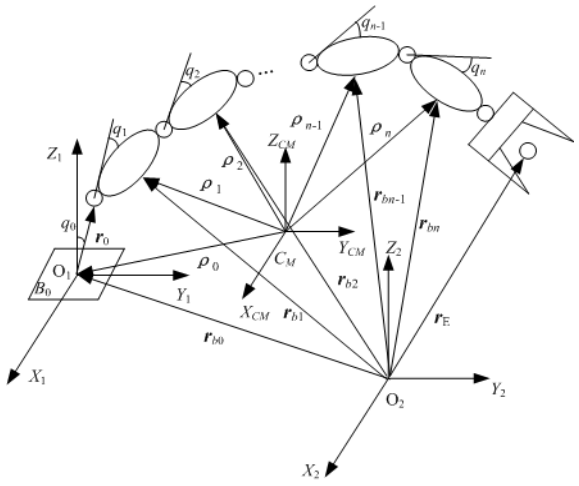


Fig. 1. The model of the space free-float redundant robotic manipulator with *n*-DOF.

Coordinate system and the symbols are defined as follows:

O_1-$X_1Y_1Z_1$ is the based coordinate system; O_2-$X_2Y_2Z_2$ is the inertial coordinate system; O_{CM}-$X_{CM}Y_{CM}Z_{CM}$ is the centroids coordinate system; B_0 is the base of the space free-float redundant robotic manipulator, $\boldsymbol{q} = [q_1,q_2,q_3 \ldots q_n]$ is the joint variables in joint space, $\boldsymbol{r}_i$ is the vector from the coordinate system origin to the centroid of the i^{th} link in the inertial coordinate system, m_0 is the mass of B_0, m_i is the mass of the i^{th} link, $\boldsymbol{l}_i$ is the position vector form the i^{th} joint to the $(i+1)^{th}$ joint, $\boldsymbol{\omega}_0$ is the angular velocity of B_0, $\boldsymbol{k}_i$ is the unit vector of the i^{th} link axis direction in the inertial coordinate system, $\boldsymbol{p}_i$ is the position vector of the i^{th} joint in the inertial coordinate system, I_i is the moment of inertia that the i^{th} link relative to the center of mass in the inertial coordinate system, E_3 is the unit matrix of 3.

2.2. The Space Redundant Robotic Manipulator Kinematics Equations

The space redundant robotic manipulator end-effector position can be expressed as:

$$\boldsymbol{r}_E = \boldsymbol{r}_{b0} + \boldsymbol{r}_0 + \sum \boldsymbol{l}_i, \tag{1}$$

Differentiate the formula (1) on time; the space redundant robotic manipulator end-effector velocity can be obtained:

$$\dot{\boldsymbol{v}}_E = \dot{\boldsymbol{r}}_E = \dot{\boldsymbol{r}}_{b0} + \boldsymbol{\omega}_0 \times (\dot{\boldsymbol{r}}_E - \dot{\boldsymbol{r}}_0) + \sum_{i=1}^{n} [\boldsymbol{k}_i \times (\boldsymbol{r}_E - \boldsymbol{p}_i)]\dot{\boldsymbol{q}}, \tag{2}$$

The space redundant robotic manipulator end-effector angular velocity can be expressed as:

$$\boldsymbol{\omega}_E = \boldsymbol{\omega}_0 + \sum_{i=1}^{n} \boldsymbol{k}_i \dot{\boldsymbol{q}}, \tag{3}$$

Combined the formula (2) and (3), the space redundant robotic manipulator kinematics equations can be obtained:

$$\dot{\boldsymbol{x}}_E = \boldsymbol{J}_{O_1} \dot{\boldsymbol{x}}_{O_1} + \boldsymbol{J}_{O_2} \dot{\boldsymbol{q}}, \tag{4}$$

where $\boldsymbol{x}_E = [\boldsymbol{v}_E \quad \boldsymbol{\omega}_E]^{\mathrm{T}}$, $\boldsymbol{x}_0 = [\boldsymbol{v}_0 \quad \boldsymbol{\omega}_0]^{\mathrm{T}}$,

$$\boldsymbol{J}_{O_1} = \begin{bmatrix} I_3 & (\boldsymbol{r}_E - \boldsymbol{r}_{O_2})^{\times} \\ 0 & I_3 \end{bmatrix}, \quad \boldsymbol{J}_{O_2} = \begin{bmatrix} \sum_{i=1}^{n} [\boldsymbol{k}_i \times (\boldsymbol{r}_E - \boldsymbol{p}_i)] \\ \sum_{i=1}^{n} \boldsymbol{k}_i \end{bmatrix},$$

'×'is an operator, which means that the anti-symmetric matrix of a vector.

2.3. The Space Redundant Robotic Manipulator Kinematics Equations

The free-floating space redundant robotic manipulator is in microgravity environment, ignoring other interference, and then the free-floating space redundant robotic manipulator is momentum conservation, assuming the initial momentum of the

robotic manipulator system is 0, the free-floating space redundant robotic manipulator linear momentum and angular momentum are as follows respectively:

$$\sum_{i=0}^{n} m_i \dot{\boldsymbol{r}}_i = 0 , \tag{5}$$

$$\sum_{i=0}^{n} (I_i \boldsymbol{\omega}_i + m_i \boldsymbol{r}_i \times \dot{\boldsymbol{r}}_i) = 0 , \tag{6}$$

Differentiate the formula (5) and (6) on the time, then substituted into formula (4), the follows is available:

$$\dot{\boldsymbol{X}}_E = (\boldsymbol{J}_{O_1} \boldsymbol{J}_B + \boldsymbol{J}_{O_2}) \dot{\boldsymbol{q}} = \boldsymbol{J}_E \dot{\boldsymbol{q}} , \tag{7}$$

where $\boldsymbol{J}_E = \boldsymbol{J}_{O_1} \boldsymbol{J}_B + \boldsymbol{J}_{O_2}$ is the free-floating space redundant robotic manipulator generalized Jacobian matrix, the generalized Jacobian matrix describes the relationship between the robotic manipulator end-effector linear and angular velocities and the joints velocities.

The free-floating space redundant robotic manipulator total kinetic energy is [15]:

$$E = \frac{1}{2} \sum_{i=0}^{n} (\boldsymbol{\omega}_i^{\mathrm{T}} I_i \boldsymbol{\omega}_i + m_i \dot{\boldsymbol{r}}_i^{\mathrm{T}} \dot{\boldsymbol{r}}_i) = \frac{1}{2} \dot{\boldsymbol{q}}^{\mathrm{T}} M \dot{\boldsymbol{q}} , \tag{8}$$

The free-floating space redundant robotic manipulator system dynamics equation can be obtained by the Lagrange equation [15] in the microgravity environment of space, ignoring the free-floating space redundant robotic manipulator system potential energy is:

$$M(\boldsymbol{q}) \ddot{\boldsymbol{q}} + C(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \tau , \tag{9}$$

where τ is the driving torque of each joint, M is the free-floating space redundant robotic manipulator symmetric positive inertial matrix, C is the free-floating space redundant robotic manipulator Coriolis force and centripetal force vector.

3. Dynamics Control Algorithm

For the free-floating space redundant robotic manipulator inverse problem, Liegeois [17] proposed the general solution of the robotic joint velocity based on generalized inverse matrix of the generalized Jacobian matrix:

$$\dot{\boldsymbol{q}} = \boldsymbol{J}_e^{+} \dot{\boldsymbol{X}}_e + \left(\boldsymbol{I} - \dot{\boldsymbol{J}}_e^{+} \right) \dot{\boldsymbol{\phi}} , \tag{10}$$

where $\boldsymbol{J}_e^{+}$ is the generalized inverse matrix of the generalized Jacobian matrix, $\boldsymbol{X}_e$ is the desired trajectory of the end-effector, $\boldsymbol{\varphi}$ is an arbitrary vector.

Differentiate the formula (10), the formula (11) can be available, that is:

$$\ddot{\boldsymbol{q}} = \boldsymbol{J}_e^{+} (\ddot{\boldsymbol{X}}_e - \dot{\boldsymbol{J}}_e \dot{\boldsymbol{q}}) + (\boldsymbol{I} - \boldsymbol{J}_e^{+} \boldsymbol{J}_e) \ddot{\boldsymbol{\phi}} , \tag{11}$$

Introduction the follow control:

$$\boldsymbol{\tau} = C(\boldsymbol{q}, \dot{\boldsymbol{q}}) + M(\boldsymbol{q}) \boldsymbol{\mu} , \tag{12}$$

Compare the dynamic equations of the free-floating space redundant robotic manipulator, and have:

$$M(\boldsymbol{q}) \ddot{\boldsymbol{q}} = M(\boldsymbol{q}) \boldsymbol{\mu} , \tag{13}$$

$\boldsymbol{M}$ $(\boldsymbol{q})$ is an invertible matrix, the formula (13) equivalent to a linear time-invariant system of decoupling.

$$\ddot{\boldsymbol{q}} = \boldsymbol{\mu} , \tag{14}$$

Introduction PD controls:

$$\boldsymbol{\mu} = \ddot{\boldsymbol{X}}_e + \boldsymbol{k}_v (\dot{\boldsymbol{X}}_e - \dot{\boldsymbol{q}}) + \boldsymbol{k}_p (\boldsymbol{X}_e - \boldsymbol{q}) , \tag{15}$$

where $\boldsymbol{k}_v$ and $\boldsymbol{k}_p$ are the feedback gain matrixes.

As long as $(\dot{\boldsymbol{X}}_e - \dot{\boldsymbol{q}}) \to 0$ and $(\boldsymbol{X}_e - \boldsymbol{q}) \to 0$, the chaotic motion control is realized, then

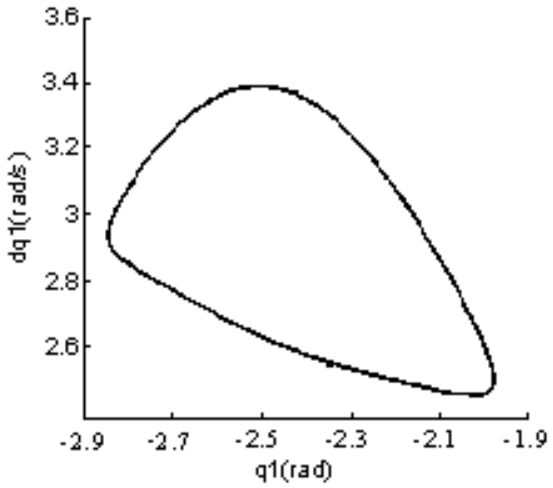
$$\begin{aligned} \boldsymbol{\tau} = M(\boldsymbol{q}) \{ \boldsymbol{J}_e^{+} [\boldsymbol{X}_e + k_v (\boldsymbol{X}_e - \boldsymbol{q}) + \\ k_p (\boldsymbol{X}_e - \boldsymbol{q}) - \boldsymbol{J}_e \boldsymbol{q} + \boldsymbol{\phi}] \} + C(\boldsymbol{q}, \boldsymbol{q}) \end{aligned} , \tag{16}$$

4. Simulation Analysis

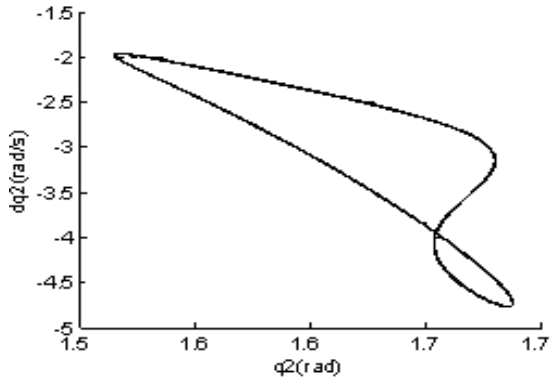
The three joints free floating space redundant robotic manipulator operated plane motion which is taken as an example and computer numerical simulation is made in this paper.

Simulation requires the end-effector moving by desired trajectory. System parameters are as follows: the body mass is m_0=2 kg, each link mass are m_1= m_2= m_3=1 kg, the body rotary inertia is I_0=2 kg/m^2, each link rotary inertia are I_1=0.3 kg/m^2 I_2=0.2 kg/m^2 I_3=0.1 kg/m^2, the length of links are l_1= l_2= l_3=1 m, the distance from the body center of mass to the first joint is l_0=1 m, position vector of the body center of mass in inertial coordinate system is $\boldsymbol{r}_C$=(0,0.2), the desired trajectory is: $\boldsymbol{X}_e$=[1+0.5cos(2πt), 2+0.5cos(2πt)], there exist the chaotic motion in the self-motion of the free-floating space redundant robotic manipulator [8].

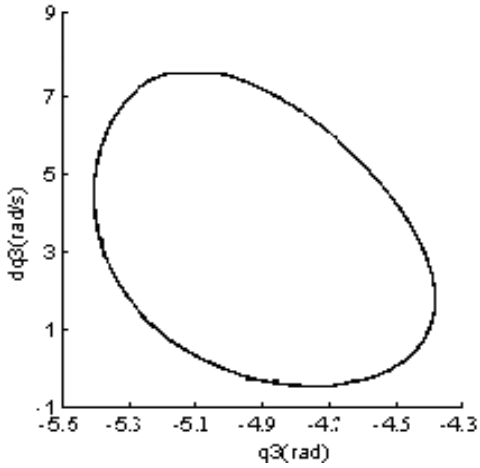
For the chaotic motion existing in the self-motion of the free floating space redundant robotic manipulator, adding the control and simulating, the phase diagrams of the joints (Fig. 2) and the Poincare section diagrams of the joints (Fig. 3) are obtained.



(a) The phase diagram of q_1



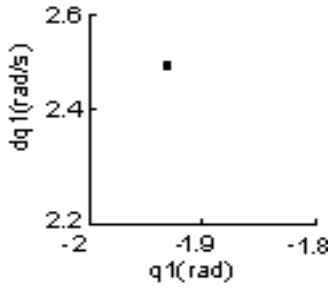
(b) The phase diagram of q_2



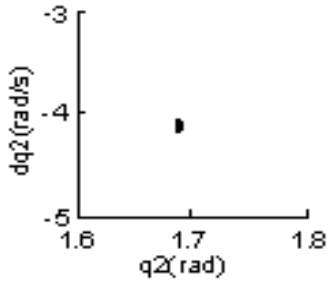
(c) The phase diagram of q_3

Fig. 2. The phase diagrams of the robotic manipulator joint after controlling.

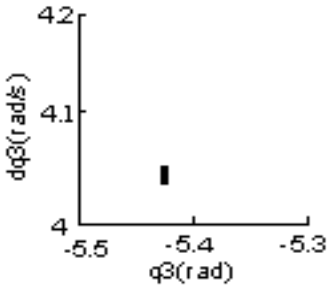
When the free floating space redundant robotic manipulator joints phase diagram is a closed curve, and Poincare section diagram is a point, the free floating space redundant robotic manipulator joints motion is periodic according to the theory of chaotic motion [18], that is, the chaotic motion can be controlled by the dynamics control algorithm.



(a) The Poincare section diagram of q_1



(b) The Poincare section diagram q_2



(c) The Poincare section diagram of q_3

Fig. 3. The Poincare section diagrams of the robotic manipulator joint after controlling.

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