On Orbit Capture and Control of Space Manipulator Based on Magneto Rheological

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Abstract. With the rapid development of space technology, the performance and technology of spacecraft is in the continuous improvement. The key technology for the non-cooperative target satellite on-orbit capture and control becomes very important. For the question of on orbit capturing a non-cooperative target, a method based on Magneto Rheological (MR) damper is proposed. There are many successful applications of MR damper in ground-base and aviation systems. However, the application of this device on a space manipulator has not been addressed yet. In this paper, A 6DOFs space robot is built in Maplesim, and analyses the kinematic and dynamic model, and the component of MR damper is also created, after simulation, the results shows that the angular velocities of joints and base has been smoothly dampen. Although the control algorithm is simple, it’s very valuable to use the MR damper in capture non-cooperative target.

1. Introduction

With the rapid development of space technology, the performance and technology of spacecraft is in the continuous improvement\cite{1}. At the same time, its organizational structure is also increasing complexity. In this case, to ensure the spacecraft can work more lasting and stable in complex space environment, which is need to develop the technology of on-orbit service, therefore, the key technology for the non-cooperative target satellite on-orbit capture and control becomes very important.

There exist several methods for on-orbit capture of non-cooperative target. Yoshikawa et al\cite{2} proposed the use of impedance control algorithm to capture non-cooperative target, and describes the conditions to ensure that the target is not pushed away after collision. Nenchev\cite{3-4} proposed the use of "Reaction null space" control algorithm to process the collision of coupled angular momentum, and this method can effectively decoupling the dynamic of manipulators and the base, limiting the base attitude in a small value within the scope, reducing the angular velocity of joints. Cong Peichao proposed a method for planning the configuration of space manipulator before arrest so that the angular momentum of system caused by collision force is zero. Although these methods are different in detail, most of them use the same fundamental approach, which is based on the dynamic model and different control algorithms. Because of the complex environment in space, the boundary conditions when capturing the target are very demanding; using control algorithms mentioned above may result to fail.
To overcome the problem of capturing a non-cooperative target, each joint of the space manipulator can be install an active damping device. According to condition at the contacting moment, and the rotational velocity of the target, the MR damper can generate the damping torque to protect the manipulator and base from damage during and after impact.

2. Kinematic And Dynamic Model ANALYSIS

2.1 Kinematic Model
In order to establish the kinematics model, we take the universal joint as two degrees of freedom joints and a zero-length link which is shown in Figure 1. The joints \( J_i \) are a single revolute for pitch direction; \( J'_i \) for yaw direction; and \( L_i \) equal to the length of link \( i \); \( L'_i \) equal to zero.

![Figure 1. The equivalent configuration of space manipulator](image)

We assume the space manipulator demonstrated in this paper is the free-floating system, and then a simplified model of space manipulator system is shown in Figure 2. From this, it can be seen that the vector from the inertial fixed origin O to i body’s centre of mass (CM).

![Figure 2. A simplified models of space manipulator and its end-effect](image)

Because there is no external force action on the system, the mass centre of the system is not changed, the linear momentum of system is conservational, and then we have the following formulation.

\[
\sum_{i=0}^{N} m_i r_i = M r_g
\]  

From (1), we can derive position vector for the mass centre of base:

\[
r_0 = r_g - \frac{(m_1 + \cdots + m_n)(b_n + a_n)}{M} - \cdots - \frac{m_n (b_{n-1} + a_n)}{M}
\]  

Then we can get the end-effector position vector:

\[
P_e = r_g + \frac{m_j b_n}{M} + \frac{m_j a_1}{M} + \frac{(m_j + m_i) b_i}{M} + \cdots + \frac{(m_j + \cdots + m_{n-1}) a_n + b_n}{M}
\]  

While the VM link \( \hat{b}_i \) and \( \hat{a}_i \) have the following formulation:
\[ \hat{b}_i = \sum_{k=0}^{i-1} \frac{m_k}{M} b_i, \hat{a}_i = \sum_{k=0}^{i-1} \frac{m_k}{M} a_i \]  

(4)

2.2 Dynamic Model

There are several mature methods for kinematics model of traditional space robot, such as the Lagrange method and Newton-Euler method. The paper uses the Lagrange method to describe the 5-links space manipulator.

The dynamic model of space manipulator should also be considered as the two degree of freedom joints and a zero-length link. According to the kinematic formulation in section 2.1, we have the following equations:

\[ \omega_i = \omega_0 + \sum_{k=1}^{i} \dot{z}_k \dot{\theta}_k \]  

(5)

\[ \dot{v}_i = \dot{r}_i = v_0 + \omega_0 \times (r_i - r_0) + \sum_{k=1}^{i} \{ \dot{z}_k \times (r_i - p_k) \} \dot{\theta}_k \]  

(6)

Then, the kinetic energy of whole system can be described as follow:

\[ T = \frac{1}{2} \sum_{i=0}^{n} (\omega_i^T I_{i} \omega_i + m_i v_i^T v_i) \]  

(7)

Combining (5), (6), (7) and making the transfer, the following equations are obtained:

\[ ME \quad M\dot{r}_i \quad J_{\omega_i} \quad J_{\theta_i} \quad J_{v_i} \quad H_{\omega_i} \quad H_{\theta_i} \quad H_{v_i} \quad \dot{\omega}_0 \quad \dot{\theta}_0 \quad \dot{v}_0 \]

\[ \begin{bmatrix} M_{\omega_0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & M_{\theta_0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & H_{\omega_0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & H_{\theta_0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & H_{v_0} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & H_{v_0} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & J_{\omega_0} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & J_{\theta_0} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & J_{v_0} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & J_{v_0} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & J_{v_0} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & J_{v_0} \\ \end{bmatrix} \begin{bmatrix} \dot{\omega}_0 \\ \dot{\theta}_0 \\ \dot{v}_0 \\ \end{bmatrix} = \begin{bmatrix} F_b \\ J_{\omega_0} \\ J_{\theta_0} \\ \end{bmatrix} \]

(8)

where

\[ H_m = \sum_{i=1}^{n} (J_{\omega_i} I_{\theta_i} + m_i J_{\omega_i} J_{\theta_i}) \]

Combining (8) into the Lagrange equation as:

\[ \begin{bmatrix} H_b & H_m \\ H_{\theta_0} & H_{v_0} \end{bmatrix} \begin{bmatrix} \dot{\omega}_0 \\ \dot{\theta}_0 \\ \end{bmatrix} + \begin{bmatrix} c_b \\ c_m \end{bmatrix} = \begin{bmatrix} F_b \\ \tau_m \end{bmatrix} + \begin{bmatrix} J_{\omega_0} \\ J_{\theta_0} \\ J_{v_0} \end{bmatrix} F_e \]

(9)

where the \( F_b \) are the Forces and moments for the base; \( F_e \) are the external forces and moments acting on the manipulator; \( \tau_m \) are the driving torques; \( c_b, c_m \) are the nonlinear force, including centripetal force and Coriolis force.

In this section, the dynamic model is analysed in MATLAB for mathematical modelling, and simulated in Maplesim for verification respectively. The results from MATLAB and Maplesim are discussed. The subsystem of base and manipulator built in Maplesim is shown in Figure 3.

Figure 3. Subsystem of base and manipulator in Maplesim

In this simulation, the each torque of joints is 0.01N, and the range of simulation time is 10s. Then analyse the dynamic model of space model in MATLAB and Maplesim respectively, and can obtain
the angular velocity of base in three axes. Figure 4 shown that, the result of numerical calculation in MATLAB is almost same with the result of simulation in Maplesim. So the mathematical model of the space manipulator has a high accuracy.

Figure 4. Angular velocity of base in X, Y, Z axis

3. On orbit Capture and Control Based on MR damper

3.1 Characteristics and Model of MR damper

Magneto Rheological Fluid (MRF) is a smart material which can be controlled by the external magnetic field. Through the effect of external magnetic field, the MRF can change from a free-flowing state into a solid-like; after removing the magnetic field, the MRF can return to a free-flowing state, just as shown in Figure 5.

Figure 5. Effect of MRF

There are many researchers which have investigated the modelling of MRF, such as the Bingham model, Herschel-Bulkley model, Bouc-Wen model, the properties, modelling were demonstrated in details by Jolly. The paper mainly focuses on the implementation of MR damper to solve the problem of on-orbit capture by space manipulator. According to the result of Wei Zhou[5-6], the modified mathematical dynamic model is formulated as follows which is based on the Bingham model.

\[
\tau = f_o \cdot \left(1 - \exp\left(-\alpha \text{abs} (\omega_{rel})\right)\right) \cdot \text{sgn} (\omega_{rel}) + c_o \cdot \omega_{rel} + \beta
\]

\[
f_o = f_a + f_b \cdot P
\]
c_0 = c_a + c_b \cdot P \quad \quad \quad \quad (12)

\dot{P} = \gamma \cdot (I - P) \quad \quad \quad \quad (13)

3.2 On orbit Capture Based on Magneto Rheological

In this section, the simulation model and the results from the simulation study are discussed. The space robot is consisted of the base; the manipulators; and the target satellite. As shown in Figure 6, the target is connected rigidly by the gripper to the end-effector at the instant of capture, and the initial torque generated by contact is set to 2Nm at each axis. The joints have been equipped with the MR damper, while the base isn’t controlled by the base mounted actuators.

Figure 6. Configuration of the space robot

In this paper, the space robot models are created in Maplesim, and the parameter values are given in Table 1.

Table 1. Inertia parameters of space robot

| Para   | Mass(Kg) | Inertia tensor(Kgm^2) |
|--------|----------|-----------------------|
| Base   | 320      | [25 18 24]            |
| link1  | 11.5     | [0.06 0.13 0.11]      |
| link2  | 7.0      | [0.02 1.28 1.28]      |
| link3  | 10.3     | [0.12 0.15 0.05]      |
| link4  | 7.5      | [0.53 0.46 0.08]      |
| link5  | 10.5     | [0.11 0.14 0.04]      |
| target | 100      | [7.24 8.17 7.38]      |

To illustrate the performance of MR damper, the numerical simulation results on capture a non-cooperative target with a free-floating space manipulator installed the MR damper of the proportional feedback control law are shown in Figure 7.

Figure 7. Relative angular velocity of joint and the base
The results presented that using MR damper to solve the on-orbit capture problem can really work. Under the effect of torque generated by MR damper, the relative angular velocity of joint has been smoothly dampen to zero. The angular velocity of base also has been decay from impulse to harmonic.

4. Conclusion
For the question of on-orbit capturing a non-cooperative target, a method based on MR damper is proposed. A 6DOF model of space model and component of MR damper are created in Maplesim. Although the control algorithm is simple, it’s very valuable to use the MR damper in capture non-cooperative target.

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