Target Capture for Free-Floating Space Robot Based on Binocular Stereo Vision

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Abstract: As the dynamics of free-floating space robots are highly nonlinear, strongly coupled and
nonholonomic constrained, the control methods for the terrestrial robot are not suitable for the free-floating
space robot. At present, the control methods for the free-floating space robot are based on accurate dynamic
model and need parameters identification. In this study, the dynamic model of the free-floating space robot is
established and the binocular stereo vision feedback method to overcome the nonholonomic constrained
characteristics that caused by the linear and angular momentum conservation theory is proposed. Then the free-
floating space robot motion control method based on acceleration decomposition method is designed. Finally,
the software of the free-floating space robot target capturing based on binocular stereo vision is developed
and simulated. The simulation results show that the free-floating space robot based on binocular stereo vision can
track a moving target in real time and ultimately can complete the target capture mission. The proposed control
method provides a new effective method for the free-floating space robot capturing the target and avoiding the
complex process of parameters identification for the space robot and also can effectively prevent the
manipulator of the space robot in collision with the target.

Key words: Nonholonomic constrained, dynamic model, parameter identification, acceleration decomposition,
real time

INTRODUCTION

The third step of manned space flight is to build a
large space station for astronauts long-term residence, but
the future of the large space station is a combination of
many cabin space station and track complexes. At
present, the assembly of the large space station is
generally by the use of space robot to implement
capturing and docking the cabins and track complexes to
instead the astronauts to complete the dangerous or
impossible tasks. At the same time, the space robot also
can do the recovery, repair and maintenance of the
satellite. However, these activities are based on precise
robot motion control and compare with the traditional
fixed based robots the base of the free-floating space
robot is moveable and one mainly difference is that the
base body of the free-floating robot has six degrees of
freedom that the control methods for terrestrial robot can
not be easily applied to free-floating space robot directly
(Wen-fu et al., 2009). The position and posture of the
base body would change when the free-floating space
robot is moving its manipulator to the position to capture
a target that take a great challenge to the control of the
free floating space robot. Therefore, it has received the
domestic and foreign scholars’ great attention.

Yoshida (2003) derived the general form of the
Jacobian matrix of the space robot by using the
conservation of the angular momentum theorem and
based this new form generalized Jacobian matrix a rescaled
motion rate control method is proposed. In the ETS-VII
validated the control method based the generalized
Jacobian matrix. Belousov et al. (2005) proposed a motion
planning method by two iterative, for a wide range space
robot based on complex dynamics. Huang et al. (2006),
Wenfu et al. (2007) and Xu et al. (2007) proposed a
control method for free-floating space robots that can
track, approach and capture the target in Cartesian space
with the spiral trajectory.

In this study, the target capturing for free-floating
space robot based on binocular stereo vision
(Malamas et al., 2003, Van der Zwaan et al., 2002) is
studied and the method does not require accurate
modeling of the system with the external feedback
(Chaunette and Hutchinson, 2008). In the general
methods, the feedback is used to implement the target
capturing avoid identifying the parameters of the free-
floating space robot system. In the visual servicing
control system a computer is employed for processing the
acquired images. This is achieved by applying special
purposed image processing analysis and classification

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software. One or more cameras placed at the scene under inspection usually acquire images. And the main problem of the machine vision task is to understand what kind of information the machine vision system is to retrieve and how this is translated into measurements or features extracted from images (Ruf and Horuda, 2000). There are two methods to design the visual servoing system (Christie et al., 2005). One is image-based visual servoing method and the other is position-based visual servoing method. Usually, the position of the cameras are fixed but in the free-floating binocular stereo vision control system, the position of the cameras mounted on the base body of the space robot is changing all the time that takes a great challenge to the space robot system. In this study, the external feedback binocular stereo vision device is used to calculate the target position in real-time for the control system to compensate for the error of the conservation of the momentum caused by the movement of the free-floating space robot.

**THE DYNAMICS OF FREE-FLOATING SPACE ROBOT**

Consider an n degrees of freedom manipulator with free-floating base body which considered as link n+1, as shown in Fig. 1 and each joint of the manipulator is a single degree of freedom, it can be rotational or translational joint. Based on Lagrange equations the free-floating space robot dynamic equations can be found by Hong-Tao and You-Lun (2000) and Fu-Yang et al. (2010). The linear and angular momentum conservation equations of the free-floating space robot are as follows:

\[
\begin{align*}
\sum_i \int_0^1 \rho_i \xi_i \, dx_i + \sum_i m_i \xi_i \, dx_i + m_n \xi_n &= L_n \\
\sum_i \int_0^1 \rho_i \xi_i \, dx_i + \sum_i m_i \xi_i \, dx_i + \sum_k J_{ik} \xi_k &= I_n \\
\sum_i \int_0^1 \rho_i \xi_i \, dx_i + J_i \, \omega_i + m_n \xi_n &= \mathbf{L} \cdot \mathbf{r} - L_i
\end{align*}
\]

where, \( \rho \) denotes the density of link i, \( m \) denotes the mass of link i, \( \xi \) drives, actuators and other rigid bodies, \( J_i \) denotes the mass of the base body of the free-floating space robot, \( P \) denotes the inertial tensor of unit length of the link i according the mass centre of the link i, \( J_r \) denotes the inertia tensor of the base body of the free-floating space robot according to the mass centre of the base body, \( L \), and \( L_r \) denote the initial linear and angular momentum of the free-floating space robot system which make the degrees of freedom increase to \( n+6 \).

**THE DESIGN OF BINOCULAR STEREO VISION**

The binocular stereo vision is based on the parallax principle that get the three dimensional geometric information of the object by multiple images. In the machine vision system, the binocular stereo vision system is generally comprise of two or more cameras apart at some distance with different angles or with one movable camera at different place taking two different images. The parallax principle is based on the triangular method and the projectional transformation to recover the three dimensional geometric objects. Although, the real scene is three dimensional, the image could be two-dimensional or three-dimensional. When we do not need to determine the depth of the scene or scene features, we can use two dimensional images, for example, in determining the contours of the object or image side that we do not need the depth information of each point of the objects, so we could use the two dimensional image. The three dimensional images processing is mainly used for those that need motion detection, depth measurements, remote sensing, relative positioning and navigation during the operation. In the free-floating space robot binocular stereo vision control system, the three dimensional images are used to calculate the position and posture of the target and feedback to the robot control system for the space robot approaching and capturing the target.

Assumed that in the space there is a target point \( p \). Points \( p \) and \( p_i \) denote the points in the image coordinates of camera \( C_i \) and camera \( C_i \) respectively, and the projection matrix (Shuqin et al., 2005) of the cameras are \( M_i \) and \( M_s \). \( q_i(x, y, z) \) denotes the coordinate system of the base body of the free-floating space robot and according to the perspective projection matrix.

Fig. 1: The free-floating space robot
transformation (Guangjun, 2004) could obtain equations as follows:

\[
\begin{bmatrix}
  x_1 \\
  y_1 \\
  z_1 \\
  \\
  x_2 \\
  y_2 \\
  z_2 \\
\end{bmatrix} = \begin{bmatrix}
  m_1^1 & m_2^1 & m_3^1 & m_4^1 & x_1 \\
  m_1^2 & m_2^2 & m_3^2 & m_4^2 & y_1 \\
  m_1^3 & m_2^3 & m_3^3 & m_4^3 & z_1 \\
  m_1^4 & m_2^4 & m_3^4 & m_4^4 & 1 \\
\end{bmatrix} \begin{bmatrix}
  x_2 \\
  y_2 \\
  z_2 \\
  1 \\
\end{bmatrix}
\]

The geometry locations of the two CCD cameras are shown in Fig. 2 \((u_0, v_0, 1)\) and \((u_2, v_2, 1)\) denote homogeneous coordinates of the points \(p_0\) and \(p_2\) in the image coordinate systems of the cameras \(C_0\) and \(C_2\), respectively and \((x_0, y_0, z_0)\) denotes homogeneous coordinate of point \(p\). From Eq. 3, the parameters \(z_1\) and \(z_2\) can be eliminated and could obtain 4 linear equations:

\[
\begin{align*}
(u_2 m_1^1 - m_2^1) x_1 + (u_2 m_1^2 - m_2^2) y_1 + (u_2 m_1^3 - m_2^3) z_1 - m_2^4 - u_m^2 m_4^2 &= 0 \\
(v_2 m_1^1 - m_2^1) x_1 + (v_2 m_1^2 - m_2^2) y_1 + (v_2 m_1^3 - m_2^3) z_1 - m_2^4 - v_m^2 m_4^2 &= 0 \\
(u_0 m_1^1 - m_2^1) x_1 + (u_0 m_1^2 - m_2^2) y_1 + (u_0 m_1^3 - m_2^3) z_1 - m_2^4 - u_m^1 m_4^1 &= 0 \\
(v_0 m_1^1 - m_2^1) x_1 + (v_0 m_1^2 - m_2^2) y_1 + (v_0 m_1^3 - m_2^3) z_1 - m_2^4 - v_m^1 m_4^1 &= 0
\end{align*}
\]

From the analytic geometry theorem, combining two plane equations we could get a space linear equation. The geometric meaning of Eq. 3 is the line \(o_1 p_1\) and line \(o_2 p_2\); and the space point \(p(x, y, z)\) is the intersection point of the line \(o_1 p_1\) and the line \(o_2 p_2\) by which we could calculate the coordinate of point \(p\). For the posture of the target, we could measure the four points of a square ABCD to calculate the posture; the posture can be calculated by following equations:

\[
\begin{align*}
o_x &= \arcsin \left( \frac{(y_2 - y_0) + (y_2 - y_0)}{(x_2 - x_0) + (x_2 - x_0)} \right) \\
o_y &= \arctan \left( \frac{(z_2 - z_0) + (z_2 - z_0)}{2L} \right) \\
o_z &= \arctan \left( \frac{(x_2 - x_0) + (z_2 - z_0)}{L(1 - \sin^2 \theta)} \right)
\end{align*}
\]

where, \(L = |AB|\) denotes the side length of the square ABCD.

**THE CONTROL SYSTEM OF SPACE ROBOT**

In the robot kinematics, the position and posture of robot end-effector could be obtained from solving the robot kinematic equations and the turning angle of each joint can be calculated when the robot end-effector is moving. The movements of robot joints are not independent but associational and coordinational and the control system is actually achieved through the joint serving systems. The movement of robot end-effector decomposed to each joint velocity, acceleration, force and torque and each joint is controlled independently. In this study, the decomposition acceleration control method with binocular stereo vision feedback is used to control the free-floating space robot capturing the target. The decomposition acceleration control method requests drivers of each joint simultaneously to move at calculated acceleration that to guarantee the robot end-effector moving smoothly and stably in Cartesian coordinate. Before control the robot, we need to decouple the position and posture of the robot end-effector into joint angle acceleration and then control the joints of the space robot (Jifeng, 2006).

Supposed that the robot has \(n\) degrees of freedom, and the position and posture of the end-effector in the Cartesian coordinates in vector form are written as follows:

\[
X(t) = [P, P, P, \psi, \theta, \phi]^T
\]

The generalized robot joint coordinate vector could be defined as:

\[
q(t) = [q_1, q_2, ..., q_n]^T
\]

The relationship between Eq. 5 and Eq. 6 are:

\[
X(t) = f(t)
\]

Supposed that the robot has \(n\) degrees of operational space freedom and the relationship of joint angle and Cartesian coordinates are written in nonlinear function Eq. 7. Derivate Eq. 7 we could obtain:
where, $j(q)$ denotes the generalized Jacobian matrix of joints, defined as:

$$J_j = \frac{\partial f_i}{\partial q_j}, 1 \leq j \leq n, 1 \leq i \leq m$$

(9)

$x(t)$ denotes the desired velocity of the robot end-effector in Cartesian coordinate, $q(t)$ denotes the joint velocity in the joint space coordinate and Eq. 9 has established the relationship of the two velocities. When degrees of freedom of the robot in operational space is equal to the degrees of freedom in robot joint space, the robot is non-redundant and the inverse of generalized Jacobian matrix can be calculated directly as follows:

$$q(t) = J^{-1}(q)x(t)$$

(10)

When $m < n$, the robot is redundant and the generalized Jacobian matrix does not exist. According to the generalized inverse matrix theory, we could obtain:

$$\ddot{q}(t) + J^T(q)\ddot{x}(t)$$

(11)

$j^T(q)$ denotes the inverse generalized Jacobian matrix. When $j(q)$ has the full rank, we could obtain following equation:

$$J^T(q) = J(q)[H(q)J(q)]^{-1}$$

(12)

Derivate Eq. 12, we could obtain the acceleration of the robot end effector, written as follows:

$$\ddot{x}(t) - J(q)\ddot{q}(t) + j(q)\dot{q}(t)$$

(13)

Equation 13 denotes the relationship between the acceleration of joints in Cartesian coordinate and in joint space coordinate, in fact, the goal of acceleration control method is to achieve the error between the actual and desire position and posture of robot end-effector converging to zero, supposed that:

$$e = x_d - x$$

(14)

where, $e$ denotes the error between the actual and desire position and posture of the robot end-effector, $x_d$ and $X$ denote the desire and actual position and posture of the robot end-effector, respectively. To meet the requirement of the converging condition that must satisfy:

$$\dot{e} + k_1e + k_2e = 0$$

(15)

where, $k_1, k_2$ are proportional coefficient, and should make sure that the real root of Eq. 15 is negative. With Eq 13-15, we could obtain:

$$q(t) = -k_1q(t) + J^{-1}(q)[X_d(t) + k_2\dot{X}_d(t) + k_1\ddot{X}_d(t)]$$

(16)

The closed loop acceleration decomposition control method is based on Eq. 16, if we have known the desire trajectory of the robot end-effector that is desire position, posture, velocity and acceleration of the robot end-effector, we could calculate the joint acceleration of each joint in joint space coordinate, then we could control the robot.

**SIMULATION**

In this study, the free floating space robot with a 6 degrees of freedom manipulator capturing the moving target is simulated. The free-floating space robot is modeled in Open3D and using DirectShow acquiring the images of the two cameras and the colour is used to get the position of the target in the image coordinate and at last use the OpenCV for image processing and send the position and posture of the target to the control system real-tumely to modify the movement of the manipulator.

Figure 3 is the simulation software of the target capturing of the free floating space robot. Figure 4 is the position of the target in the robot coordinate that calculated from the processed images. Figure 5 is the
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