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Hybrid Impedance/Position Control of a Free-Flying Space Robot for Detumbling a Noncooperative Satellite

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Abstract: This paper presents hybrid impedance/position control of a free-flying space robot for detumbling a noncooperative satellite. Detumbling a noncooperative satellite by a single serial-link manipulator is achieved using a novel hybrid control scheme in which position-based impedance control in the direction normal to the surface of a noncooperative satellite realizes soft contact between the end tip of the robot's manipulator and the desired contact point on the satellite, while PID position control in other directions maintains the end-tip position and orientation at the same contact point. The hybrid control scheme utilizes vectors expressed in a reference frame fixed in a noncooperative satellite. Simulation results in a two-dimensional planar case show that our approach of using the proposed hybrid impedance/position control scheme succeeded in realizing zero angular velocity of a noncooperative satellite.

Keywords: Space robot, noncooperative satellite capture, contact control, hybrid control, detumbling.

1. INTRODUCTION

Detumbling a noncooperative satellite has been a big issue in an autonomous on-orbit servicing operation. What makes this operation difficult is that, in general, a noncooperative satellite is unable to assist capture operation by a grasping fixture on the satellite's surface or attitude control. Until date, various kinds of methods have been proposed. For instance, Sugai et al. (2013) proposed contactless eddy current brake utilizing magnetic fields emitted from a space robot. Bennett (2015) proposed an electrostatic actuation method utilizing electron emission/transfer. A passive brush-type braking with active force control proposed by Nishida and Kawamoto (2011) makes use of a mechanically compliant contact.

Detumbling a noncooperative satellite by mechanical contact needs an appropriate contact force control. Two approaches are mainly adopted when using a manipulator: impedance control proposed by Hogan (1985), and hybrid force/position control proposed by Raibert and Craig (1981). The impedance control scheme realizes a soft contact, while the hybrid control scheme follows the reference profiles of both forces and positions in the directions specified. However, most studies only consider the control of precontact and/or postcontact state, and do not consider controlling the contact force itself because the contact phenomenon is highly nonlinear and difficult to describe. Ma paid great attention to the importance of contact control, and performed various in-orbit contact dynamics analyses, for instance, Ma (1995). Yoshida et al. (2004) tackled the contact problem, and proposed the concept of impedance matching when using impedance control in the orbit. Nakanishi et al. (2010) proposed the concept of virtual mass when applying impedance control to predict the post-contact state.

The first author had proposed impedance control of a free-flying space robot for maintaining contact with the surface of a noncooperative satellite in Uyama et al. (2012). The previous work succeeded in suppressing the postcontact relative translational velocity to zero between the end tip of the space robot and the target free-flying satellite. A desired mechanical impedance is tuned from a desired coefficient of restitution and a desired damping ratio by considering contact dynamics. However, this work assumed one-dimensional motion, and no rotation was considered because we assumed that the contact force acted through the centroid of the target satellite.

In order to detumble a noncooperative satellite, we divided the capturing problem into two parts: to realize a desired compliant contact in the direction normal to the contact surface, and to keep the end-tip position and orientation tracking at a predefined contact point. We name our approach hybrid impedance/position control of a free-flying space robot, which is realized by replacing the force controller in the conventional hybrid force/position controller by a position-based impedance controller. Choosing a reference frame fixed on a noncooperative satellite makes it simpler and easier to describe reference trajectories than to describe them with respect to the inertial frame. The sections below present the formulation of dynamics and control law, followed by validation through dynamic simulation.

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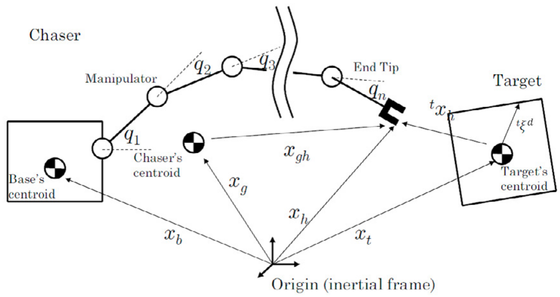

Fig. 1. Robot Model

2. DYNAMICS

This section presents the dynamics of free-flying bodies in a microgravity environment. The reference frame is taken in the inertial frame, unless otherwise specified. Bold letters and nonbold letters in equations represent matrices/vectors and scalars, respectively. From now on, we use the words "chaser" and "target" indicating a robotic satellite and a noncooperative satellite, respectively.

2.1 Assumptions

The following are the assumptions made in this work.

- All the bodies considered in this paper are rigid.
- Joints ideally react against the input torque with no time delay.
- The gravitational acceleration is set to zero.
- All the states of the chaser and the target can be measured by some means.
- All parameters, such as the inertia and centroid of the chaser and the target, are known prior to contact.
- Contact is described by a point contact.
- No frictional effect is considered at this moment.
- The end tip of the manipulator can only "push" the target and cannot "pull" the target.

2.2 Chaser dynamics

First, assuming a robot model shown in Fig. 1, we start with the dynamic equations of motion of a chaser space robot with a serial-link n-DOF manipulator, given in (Umetani and Yoshida (1989)):

$$\begin{bmatrix} \boldsymbol{F}_b \\ \boldsymbol{\tau} \end{bmatrix} = \begin{bmatrix} \boldsymbol{H}_b & \boldsymbol{H}_{bm} \\ \boldsymbol{H}_{bm}^T & \boldsymbol{H}_m \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_b \\ \ddot{\boldsymbol{q}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}_b \\ \boldsymbol{c}_m \end{bmatrix} - \begin{bmatrix} \boldsymbol{J}_b^T \\ \boldsymbol{J}_m^T \end{bmatrix} \boldsymbol{F}_h \quad (1)$$

where the dot on a variable indicates the time-derivative, and the descriptions of the variables are as follows.

$\boldsymbol{H}_b \in R^{6\times6}$	:	inertia matrix of the base
$\boldsymbol{H}_m \in R^{n\times n}$	:	inertia matrix of the manipulator
$\boldsymbol{H}_{bm} \in R^{6\times n}$	:	coupled inertia matrix of the base and the manipulator
$\boldsymbol{c}_b \in R^6$	:	nonlinear velocity-dependent term of the base
$\boldsymbol{c}_m \in R^n$	:	nonlinear velocity-dependent term of the manipulator
$\boldsymbol{J}_b \in R^{6\times6}$	:	Jacobian matrix of the base
$\boldsymbol{J}_m \in R^{6\times n}$	:	Jacobian matrix of the manipulator
$\boldsymbol{F}_b \in R^6$	:	external force/torque on the base
$\boldsymbol{F}_h \in R^6$	:	external force/torque on the end tip of the manipulator
$\boldsymbol{\tau} \in R^n$	:	joint torque
$\boldsymbol{x}_b \in R^6$	:	position and orientation of the base
$\boldsymbol{q} \in R^n$	:	joint angle of the manipulator

The end-tip velocity control of a free-flying manipulator with respect to the inertial frame becomes similar to that of a ground-based manipulator by introducing the generalized Jacobian $\boldsymbol{J}^*$ (Umetani and Yoshida (1989)) as follows.

$$\dot{\boldsymbol{x}}_h = \boldsymbol{J}^* \dot{\boldsymbol{q}} + \dot{\boldsymbol{x}}_{gh} \quad (2)$$

$$\boldsymbol{J}^* \equiv \boldsymbol{J}_m - \boldsymbol{J}_b \boldsymbol{H}_b^{-1} \boldsymbol{H}_{bm} \quad (3)$$

$\dot{\boldsymbol{x}}_h \in R^6$ is the end-tip velocity with respect to the inertial frame, and $\dot{\boldsymbol{x}}_{gh} \in R^6$ is the velocity of the gravity centroid of the entire system projected onto the end tip, defined as follows.

$$\dot{\boldsymbol{x}}_{gh} = \boldsymbol{R}_h \dot{\boldsymbol{x}}_g \quad (4)$$

$\boldsymbol{R}_h \in R^{6\times6}$ is given by the following expression:

$$\boldsymbol{R}_h = \begin{bmatrix} \boldsymbol{E}_3 & -\tilde{\boldsymbol{x}}_{gh} \\ \boldsymbol{0} & \boldsymbol{E}_3 \end{bmatrix} \quad (5)$$

where $\boldsymbol{E}_3$ is a 3-by-3 identity matrix, and $\tilde{\boldsymbol{x}}_{gh}$ is a skew-symmetric matrix. Now, the end tip motion can be computed without measuring base reaction.

Making use of the equations expressed in the joint space by using the generalized Jacobian matrix is convenient for achieving the end-tip control. The upper equation of (1) can be solved for base acceleration $\ddot{\boldsymbol{x}}_b$ and substituted into the bottom equation of (1).

$$\boldsymbol{\tau} = \boldsymbol{H}^* \ddot{\boldsymbol{q}} + \boldsymbol{c}^* - \boldsymbol{J}^{*T} \mathcal{F}_h \quad (6)$$

$$\boldsymbol{H}^* = \boldsymbol{H}_m - \boldsymbol{H}_{bm}^T \boldsymbol{H}_b^{-1} \boldsymbol{H}_{bm} \quad (7)$$

$$\boldsymbol{c}^* = \boldsymbol{c}_m - \boldsymbol{H}_{bm}^T \boldsymbol{H}_b^{-1} \boldsymbol{c}_b \quad (8)$$

where $\boldsymbol{H}^* \in R^{n\times n}$ is the generalized inertia matrix, and $\boldsymbol{c}^* \in R^n$ is the generalized nonlinear velocity-dependent term including the Coriolis and centrifugal forces.

2.3 Target dynamics

Next, the dynamic equations of motion of a target can be expressed as follows.

$$\boldsymbol{F}_t = \boldsymbol{H}_t \ddot{\boldsymbol{x}}_t \quad (9)$$

where $\boldsymbol{F}_t \in R^6$ is the external force/moment on the base; $\boldsymbol{H}_t \in R^{6\times6}$ is the inertia matrix of the base, and $\ddot{\boldsymbol{x}}_t \in R^6$ is the acceleration of the base.