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Optimal capture occasion determination and trajectory generation for space robots grasping tumbling objects

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ABSTRACT

This paper presents an optimal trajectory planning scheme for robotic capturing of a tumbling object. Motion planning of a space robot is much more complex than that of a fixed-based robot, due to the dynamic coupling between the manipulator and its base. In this work, the Path Independent Workspace (PIW), in which no dynamic singularity occurs, and Path Dependent Workspace (PDW) of the space robot are first calculated by the proposed algorithm. The motion equations of the tumbling object are formulated based on the Euler dynamics equations and the quaternion, which are used to predict the long-term motion of a grasping point on the tumbling object. Subsequently, the obtained PIW workspace and predicted motion trajectories are used to plan the trajectory of the end-effector to intercept the grasping point with zero relative velocity (to avoid impact) in an optimal way. In order to avoid dynamic singularity occurring at the capture moment, the optimal capture occasion is first determined by three proposed criterions guaranteeing the capture can be safely, reliably and rapidly performed, then the optimal trajectory of the end-effector is generated minimizing a cost function which acts as a constraint on acceleration magnitude. Simulations are presented to demonstrate the trajectory planning scheme for a space robot with a 3-degree of freedom (DOF) manipulator grasping a tumbling satellite, the results show that the manipulator end-effector can smoothly intercept the grasping point on the tumbling satellite with zero relative velocity.

1. Introduction

Since mid-1990s, space robots have made a great progress [1]. Missions like "Robot Technology Experiment (ROTEX)" [2], "Engineering Test Satellite VII (ETS-VII)" [3] and "Orbital Express (OE)" [4], etc. have been performed to demonstrate the key servicing technologies of space robots. However, all targets in these missions were cooperative with Attitude Control System (ACS). Ground observations [5] show that many defunct satellites have indeed tumbling motion, which is caused by the migration of the angular momentum from the gyros and wheels of the satellite to its body as soon as failure occurs and the long-term effects produced by the environmental perturbations. The tumbling motion makes the robotic capturing a very challenging task, in fact, robotic capturing of a tumbling satellite has yet to be attempted.

The typical process of a space robot grasping a target can be roughly divided into two phases: 1) pregrasping phase and 2) postgrasping phase. In the pregrasping phase, the manipulator moves from its home position to intercept a grasping point on the target at a rendezvous point with zero relative velocity. In the postgrasping phase, the manipulator has to bring the target to rest in such a way that the joint position and torque remain within a safe range [6]. This paper focuses on a manipulator trajectory planning scheme for pregrasping phase.

Y. Umetani and K. Yoshida [7] derived the Generalized Jacobian Matrix (GJM) of space robots, which bridged the end-effector velocity and the joint angular velocity. With the relationship between these two kinds of velocity which are in different spaces, the trajectory of the manipulator for capturing a tumbling target can be designed in two different ways: 1) the joint angular trajectories are parameterized and all capture requirements are expressed as constraints in the joint space, then a nonlinear optimization problem is solved to directly obtain the desired joint trajectories, or 2) the end-effector trajectory in the task space is first planned, then the corresponding joint velocities are calculated by solving the inverse kinematics problem. Many methods have been studied to acquire optimal joint trajectories in the joint space. M. Wang et al. [8] parameterized joint trajectories with Bézier curves, then the parametric optimization problem was solved using Particle Swarm Optimization (PSO) method. R. Lampariello et al. [9]

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studied the real-time trajectory planning for a robot to optimally catch flying target, in which the desired joint trajectories were encoded with B-splines or trapezoidal functions and the Sequential Quadratic Programming (SQP) method was employed to search the optimal solution. W. Xu et al. [10] parameterized the joint trajectories with polynomial or sinusoidal functions first. Then, the parameters were solved by an iterative Newtonian method. In all these methods, since the direct kinematics equations were used, dynamic singularities which may occur when solving inverse kinematics problem can be avoided. However, as pointed out in the paper [9], the drawback of optimizing parametric joint trajectories is that the convergence time may be long because of the required numerical iterations. Meanwhile, in the problem of a space robot capturing a tumbling target, the requirement of zero relative velocity between the end-effector and the grasping point at rendezvous moment is easily formulated in task space rather than in joint space. Some researchers focused on generating desired end-effector trajectory in task space, then the inverse kinematics equations were solved to obtain the required joint angular trajectories [11,12]. F. Aghili [12] obtained an optimal end-effector trajectory by analytically solving an optimal control problem, which can achieve zero relative velocity requirement at capturing moment. In order to obtain joint trajectories, the inverse kinematics problem had to be solved. E. Papadopoulos [13] pointed out dynamic singularities could happen when solving the problem. In this case, too large angular velocities would be needed to make the end-effector follow the desired trajectory. The author defined the Path Dependent Workspace (PDW) to contain all workspace locations that may induce a dynamic singularity. Subtract the PDW from the reachable workspace, the Path Independent Workspace (PIW) was obtained. All the points in the PIW were guaranteed not to have dynamic singularities. F. Aghili recommended to use a singularity robust scheme for inverse kinematic solution after acquiring the optimal end-effector trajectory in the task space. However, to the best of authors' knowledge, although many singularity-robust schemes have been studied [14–16], the resulting angular trajectory will cause the end-effector to deviate from desired trajectory. The deviations occur at some moments during the approaching process are allowable because they may be compensated later with proper methods, but not include the capture moment, since the capture is going to happen and the deviation could cause collision and lead to large impact force.

In this paper, we first determine the optimal capture occasion with the help of the PIW concept, then the optimal capture trajectory of the end-effector is planned by using the optimal control theory. The main advantages of the proposed scheme are that the capture can be performed without any possibility encountering dynamic singularity at the capture moment and an optimal capture trajectory can be obtained. The rest of the paper is organized as follows: In Section 2, the kinematics and dynamics equations of free-floating space robots are established, and an algorithm is proposed to analyze the space robot's workspaces; Section 3 derives the motion equations of a tumbling target, the motion trajectory of a grasping point on the target is illustrated and the key factors affecting the trajectory are analyzed. In Section 4, we propose three criterions to determine when and where is the best occasion to capture the target, then the optimal motion trajectory of the end-effector is generated using the optimal control theory. In Section 5, a case study of a space robot capturing a tumbling target is presented to demonstrate the correctness of the proposed scheme. Finally, the conclusive remarks are made at the end of the paper, in Section 6.

2. Modeling and workspace analysis of space robots

2.1. Motion equations of space robots

A space robot consists of a satellite base and an n degree of freedom (DOF) manipulator as shown in Fig. 1, whose kinematics and dynamics equations can be expressed as follows: [7].

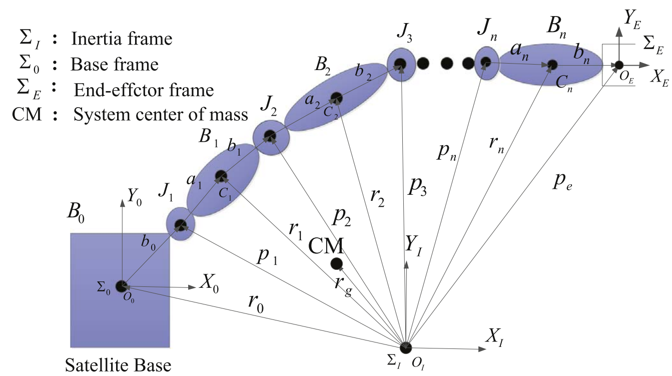

Fig. 1. Schematic of a space robot system.

$$\begin{bmatrix} \boldsymbol{v}_e \\ \boldsymbol{\omega}_e \end{bmatrix} = \boldsymbol{J}_b \begin{bmatrix} \boldsymbol{v}_b \\ \boldsymbol{\omega}_b \end{bmatrix} + \boldsymbol{J}_m \dot{\boldsymbol{\theta}} \tag{1}$$

$$\begin{bmatrix} \boldsymbol{H}_b & \boldsymbol{H}_{bm} \\ \boldsymbol{H}_{bm}^T & \boldsymbol{H}_m \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_b \\ \ddot{\boldsymbol{\theta}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}_b \\ \boldsymbol{c}_m \end{bmatrix} = \begin{bmatrix} \boldsymbol{f}_b \\ \boldsymbol{\tau} \end{bmatrix} + \begin{bmatrix} \boldsymbol{J}_b^T \\ \boldsymbol{J}_m^T \end{bmatrix} \boldsymbol{f}_e \tag{2}$$

where $\boldsymbol{v}_e$, $\boldsymbol{\omega}_e$ are the linear and angular velocity of the end-effector (the hand of the manipulator), respectively. $\dot{\boldsymbol{x}}_b = [\boldsymbol{v}_b\ \boldsymbol{\omega}_b]^{\mathrm{T}}$ is the linear, angular velocity of the base body, $\dot{\boldsymbol{\theta}}$ is the joint velocities vector of the manipulator. Other symbols' physical meanings are listed in Table 1. If not special specified, all vectors are expressed in the inertial frame.

To conserve fuel or avoid vibration of the end-effector caused by discontinuous base forces, all base satellite actuators may be turned off when the manipulator is tracking the servicing target [17]. In this case, the space robot is in the free-floating mode with external forces $\boldsymbol{f}_b, \boldsymbol{f}_e = \boldsymbol{0}$, whose dynamics equation can be simplified as Eq. (3) from Eq. (2):

$$\boldsymbol{\tau} = \boldsymbol{H}_{\boldsymbol{\theta}} \ddot{\boldsymbol{\theta}} + \boldsymbol{c}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) \tag{3}$$

where $\boldsymbol{H}_{\boldsymbol{\theta}} = \boldsymbol{H}_m - \boldsymbol{H}_{bm}^T \boldsymbol{H}_b^{-1} \boldsymbol{H}_{bm}$ is defined as “inertia tensor for free-floating space robots”. $\boldsymbol{c}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) = \boldsymbol{c}_m - \boldsymbol{H}_{bm}^T \boldsymbol{H}_b^{-1} \boldsymbol{c}_b$ is the nonlinear term about coriolis and centrifugal forces of free-floating space robots. Free-floating space robots can also have a more concise kinematics equation since they obey momentum conservation laws:

$$\begin{bmatrix} \boldsymbol{P} \\ \boldsymbol{L} \end{bmatrix} = \boldsymbol{H}_b \begin{bmatrix} \boldsymbol{v}_b \\ \boldsymbol{\omega}_b \end{bmatrix} + \boldsymbol{H}_{bm} \dot{\boldsymbol{\theta}} + \begin{bmatrix} \boldsymbol{0}^{3\times1} \\ \boldsymbol{r}_0 \times \boldsymbol{P} \end{bmatrix} \tag{4}$$

where $\boldsymbol{P}$ and $\boldsymbol{L}$ express linear and angular momentum, respectively. $\boldsymbol{r}_0$ is the position of the satellite base. Suppose the initial momentum of the free-floating space robot is $\boldsymbol{0}$, substitute Eq. (4) into Eq. (1) and eliminate $\boldsymbol{v}_b$ and $\boldsymbol{\omega}_b$ gives the following kinematics equation:

$$\begin{bmatrix} \boldsymbol{v}_e \\ \boldsymbol{\omega}_e \end{bmatrix} = \boldsymbol{J}_g \dot{\boldsymbol{\theta}} = (\boldsymbol{J}_m - \boldsymbol{J}_b \boldsymbol{H}_b^{-1} \boldsymbol{H}_{bm}) \dot{\boldsymbol{\theta}} \tag{5}$$

Table 1
Symbols of the space robot.

Symbols	Physical meanings
J_i, C_i	joint i, mass center of link i
$\boldsymbol{a}_i$, $\boldsymbol{b}_i$	position vectors from J_i to C_i and from C_i to J_{i+1}, m
m_i, M	mass of the ith link and the whole system
$\boldsymbol{H}_b$, $\boldsymbol{H}_m$	inertia matrix of base and manipulator
$\boldsymbol{H}_{bm}$	coupling inertia matrix between base and manipulator
$\boldsymbol{c}_b$, $\boldsymbol{c}_m$	vectors of velocity dependent nonlinear terms
$\boldsymbol{f}_b, \boldsymbol{f}_e$	vectors of force and torque exerted on base and end-effector
$\boldsymbol{\tau}$	torque exerted on manipulator joints, N·m
$\boldsymbol{J}_b$, $\boldsymbol{J}_m$	Jacobian matrix of base and end-effector