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Analysis of reaction torque-based control of a redundant free-floating space robot

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Abstract Owing to the dynamics coupling between a free-floating base and a manipulator, the non-stationary base of a space robot will face the issue of base disturbance due to a manipulator's motion. The reaction torque acted on the satellite base's centroid is an important index to measure the satellite base's disturbance. In this paper, a comprehensive analysis of the reaction torque is made, and a novel way to derive the analytical form of the reaction torque is proposed. In addition, the reaction torque null-space is derived, in which the manipulator's joint motion is dynamically decoupled from the motion of the satellite base, and its novel expression demonstrates the equivalence between the reaction torque null-space and the reaction null-space. Furthermore, the reaction torque acted as an optimization index can be utilized to achieve satellite base disturbance minimization in the generalized Jacobian-based end-effector Cartesian path tracking task. Besides, supposing that the redundant degrees of freedom are abundant to achieve reaction torque-based active control, the reaction torque can be used to realize satellite base attitude control, that is, base attitude adjustment or maintenance. Moreover, because reaction torque-based control is a second-order control scheme, joint torque minimization can be regarded as the optimization task in reaction torque-based active or in-active control. A real-time simulation system of a 7-DOF space robot under Linux/RTAI is developed to verify and test the feasibility and reliability of the proposed ideas. Our extensive empirical results demonstrate that the corresponding analysis about the reaction torque is correct and the proposed methods are feasible.

1. Introduction

A space robot is an important tool for space activities like target capturing, on-orbit servicing, outer space exploration, and so on. It seems to be an extension of human beings' arms, that is to say, our limitations on the field of activities are expanded by the advent of a space robot. Hence, the last 30 years have witnessed an increasing interest towards robotic applications in space.[1–5]

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Unlike a terrestrial manipulator, a space robot is always free from the influence of an external force. The coupling relationship between a satellite base and a mounted manipulator will alter the satellite's position and posture resulting in difficulty in the design of a space robot's control systems. Besides, the conventional treatment on this coupling of a free-floating space robot is always from the view of one-order differential equations: the rotational momentum conservation equation and the translational momentum conservation equation.[6–8] The former is just an integrable expression which can be transformed into a position relationship of each link of a space robot, and hence the conclusion of a free-floating space robot's invariant centroid is derived. Whereas, the latter translational momentum conservation is just a non-integrable relationship and it is also the non-holonomic constraint of a free-floating space robot. Meanwhile, in practical applications, a satellite's attitude overwhelms its position, as the attitude is so important when considering solar supplement and information communication.[9]

Furthermore, the way to deal with the satellite attitude is always a hot spot in the field of planning and control of a space robot, and to some degree, the satellite attitude adjustment or maintenance will determine the task implementation.[10,11] Therefore, path planning algorithms and motion control laws are always the footstones of autonomous control of a space robot. In literature, Dubowsky and Torres planned the trajectory of a space manipulator using an enhanced disturbance map (EDM) to minimize the base attitude disturbance.[12] They took a 2-DOF manipulator for example; however, it is difficult to obtain the EDMs of manipulators with more DOFs. Vafa and Dubowsky used a virtual manipulator model to develop path planning that reduced the base disturbance, which is called the self-correcting path planning algorithm.[13] In this method, a system is considered as a linear system with the assumption that the movement of joints is small enough. Nakamura and Mukherjee utilized Lyapunov function to achieve the regulations of both the satellite orientation and the manipulator joint angle simultaneously.[14] However, the stability of this method was mot demonstrated strictly and the planned joint angles were not smooth. Fernands et al. proposed near-optimal non-holonomic motion planning to achieve attitude control inspired by the fact that a falling cat can change its orientation in midair.[15] Nenchev et al. originally utilized the notation of reaction null-space (RNS) to achieve attitude control.[16,17] To sum up, the RNS method is the only method that can achieve both the base attitude regulation and end-effector trajectory planning simultaneously, and it has been verified in the flight experiments of ETS-VII.

The above proposed algorithms are offline or online motion control of a space robot on the basis of one-order differential motion equations. As for a space robot's autonomous control, online coordination of the motion between a satellite and a manipulator is crucial. In spite of the fact that the online application of the RNS can be achieved, the end-effector Cartesian path tracking task is limited to position or posture control. The application of the method is quiet a conservative way, and the extended ETS-VII mission is just the path tracking of predefined reactionless paths. In addition, in Cocuzza's studies,[18–20] the importance of a reaction torque has been emphasized and the corresponding three algorithms have been proposed, that is, least-squares based reaction torque control, null-space based reaction torque control, and weighted pseudoinverse based reaction torque control aimed at achieving a minimum satellite base attitude disturbance. However, the reaction torque in his studies is the torque acted on the hinge point of the first joint and the satellite base, besides the reaction torque is viewed as the optimization task in his proposed algorithms, and the subsequent experiments are made on a ground-based 3-DOF manipulator on an air-bearing table.

In addition, the dynamic coupling and mounted manipulator reaction control issues are of vital importance in path planning and autonomous control of a free-floating space robot.

The main contribution of this paper is to give a comprehensive analysis of the reaction torque acted on a satellite base's centroid. Firstly, a novel solution to get the analytical expression about the satellite base reaction torque of a free-floating space robot is proposed. Then, when an abundant DOF exists, the reaction torque can be utilized to achieve satellite attitude adjustment or maintenance, that is to say, the reaction torque is acted as a control task to achieve satellite base active control. Besides, when more DOFs are occupied, the reaction torque is viewed as an optimization task to achieve a satellite attitude disturbance minimization task. Moreover, due to the usage of second-order motion equations, the joint driving torque can be included in the optimization task.

The paper is organized as follows. In Section 2, a kinematics and dynamics model is built, and the inverse kinematics of a space robot is also explained. Then a novel approach to obtain the analytical expression of the reaction torque is developed in Section 3. Section 4 illustrates the reaction torque based inactive control for satellite attitude disturbance minimization. Section 5 shows the reaction torque based active control for satellite attitude adjustment/maintenance with joint torque optimization. In Section 6, a real-time simulator under Linux/RTAI is built and a set of experiments is made to verify the proposed algorithms. The conclusions are summarized in Section 7.

2. Motion equation of a redundant space robot

2.1. Dynamic and kinematic model of a space robot

Considering the linear and angular velocities of the base $\dot{\boldsymbol{x}}_{\mathrm{b}} = \left[\boldsymbol{v}_{\mathrm{b}}^{\mathrm{T}}, \boldsymbol{w}_{\mathrm{b}}^{\mathrm{T}}\right]^{\mathrm{T}} \in \mathbf{R}^{6\times 1}$ ($\boldsymbol{v}_{\mathrm{b}}$ is the base linear velocity and $\boldsymbol{w}_{\mathrm{b}}$ is the base angular velocity) and the angular velocity of each joint $\dot{\boldsymbol{\theta}} \in \mathbf{R}^{n\times 1}$, the equation of motion of the space manipulator system is presented as[6]

$$\begin{bmatrix} \boldsymbol{H}_{\mathrm{b}} & \boldsymbol{H}_{\mathrm{bm}} \\ \boldsymbol{H}_{\mathrm{bm}}^{\mathrm{T}} & \boldsymbol{H}_{\mathrm{m}} \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_{\mathrm{b}} \\ \ddot{\boldsymbol{\theta}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}_{\mathrm{b}} \\ \boldsymbol{c}_{\mathrm{m}} \end{bmatrix} = \begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{\tau} \end{bmatrix} \tag{1}$$

where $\boldsymbol{H}_{\mathrm{b}} \in \mathbf{R}^{6\times 6}$ is the inertia matrix of the base, $\boldsymbol{H}_{\mathrm{bm}} \in \mathbf{R}^{6\times n}$ is the coupled inertia matrix, $\boldsymbol{H}_{\mathrm{m}} \in \mathbf{R}^{n\times n}$ is the inertia matrix of the manipulator, $\boldsymbol{c}_{\mathrm{b}} \in \mathbf{R}^{6}$ is the velocity-dependent non-linear term of the base, $\boldsymbol{c}_{\mathrm{m}} \in \mathbf{R}^{n}$ is the velocity-dependent non-linear term of the manipulator, and $\boldsymbol{\tau} \in \mathbf{R}^{n}$ is the manipulator joint torque.

The motion of the free-floating space robot observes the law of momentum conservation, that is,

$$\sum_{i=0}^{n} m_i \dot{\boldsymbol{r}}_i = \mathrm{const} \tag{2}$$

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