Chinese Journal of Aeronautics, (2017), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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# Hybrid task priority-based motion control of a redundant free-floating space robot

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Received 23 December 2016; revised 9 March 2017; accepted 30 April 2017

**KEYWORDS**

Base attitude control;
Hybrid task-priority;
Motion planning;
Multiple constraints;
Redundant space robot

**Abstract** This paper presents a novel hybrid task priority-based motion planning algorithm of a space robot. The satellite attitude control task is defined as the primary task, while the least-squares-based non-strict task priority solution of the end-effector plus the multi-constraint task is viewed as the secondary task. Furthermore, a null-space task compensation strategy in the joint space is proposed to derive the combination of non-strict and strict task-priority motion planning, and this novel combination is termed hybrid task priority control. Thus, the secondary task is implemented in the primary task's null-space. Besides, the transition of the state of multiple constraints between activeness and inactiveness will only influence the end-effector task without any effect on the primary task. A set of numerical experiments made in a real-time simulation system under Linux/RTAI shows the validity and feasibility of the proposed methodology.





## 1. Introduction

With advances in space applications, space robots are essential to implement space exploration missions including assembling a space station, on-orbit servicing, space debris removal, and so on. The development of space robots impels space exploration to be efficient and safe. Hence, the last 40 years have witnessed an increasing interest towards robotic applications in space.[1–5]

Different types of space robots have different research priorities, such as the flexible issue of a manipulator with long links,[6] the configuration and control issue of a soft robot,[7] the base attitude disturbance of a free-floating space robot, and so on. Meanwhile, free-floating space robots, like manipulator mounted[8] satellites or tethered space robots,[9] have always been a focused research object in the field of space exploration. The base attitude is disturbed by the movement of a manipulator, while it is so important when considering solar supplement and information communication. The satellite attitude control task is typically achieved by the attitude control system of a satellite, so limited fuel will be consumed. Besides, the coupling relationship between a satellite base and a manipulator can be utilized to adjust or maintain the satellite attitude.[10,11] Furthermore, other degrees of freedom (DOFs) will be used to achieve a manipulator's end-effector task. In

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2017.08.009
1000-9361 

this paper, we address this issue from the view of a path planning strategy.

In literature, Dubowsky and Torres planned the trajectory of a space manipulator using an enhanced disturbance map (EDM) to minimize the disturbance of the base attitude.[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 movements of joints are small enough. Nakamura and Mukherjee utilized the Lyapunov function to achieve regulations of both the satellite orientation and the manipulator joint angles simultaneously.[14] However, the stability of this method was not demonstrated strictly and the planned joint angles were not smooth. Fernandes et al. proposed a near-optimal nonholonomic motion planning algorithm 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 base attitude control.[16]

RNS was originally proposed in Nenchev's study,[17] and it was applied to achieve a vibration suppression task, a reactionless end-point control task, and a combined motion control task. Then it was utilized to achieve reactionless manipulation or zero reaction maneuver (ZRM).[18] It was also verified in the flight experiments of ETS-VII. To sum up, the RNS method is the only real-time method that can achieve base attitude regulation and end-effector trajectory planning simultaneously. However, algorithmic singularity (AS), representation singularity (RS), and dynamics singularity (DS)[19] exist in conventional RNS-based motion planning algorithms. Some preliminary improvements on algorithmic singularity avoidance and dynamics singularity avoidance have been made,[19,20] but an algorithmic error exists. Furthermore, conventional RNS-based motion planning methods ignore physical constraints like joint limits, whereas physical constraints avoidance is of vital importance in the real-time motion control of a space robot.

In addition, singularity robust, especially AS-free, motion control for base attitude control with multiple constraints of a space robot is a new issue that should be considered. Additionally, an AS-free motion control law subject to multi constraints will give a more stable result. Besides, a task hierarchical framework will be introduced to guarantee that activated multi constraints will be transferred in the null-space of the primary task.

In this paper, a strict task priority strategy is adopted to realize singularity robust and hierarchical motion planning of a space robot;[21] besides, a non-strict task-priority strategy is also utilized to achieve multiple constraints avoidance,[22,23] and the least squares problem consisting of a multi-constraint task and an antecedent secondary task (end-effector path tracking) is implemented in the null-space of the primary task. Therefore, in this paper, a task hierarchical control algorithm for satellite base attitude control under multi constraints is derived. Besides, a null-space task compensation strategy in the joint space is proposed to give an AS-free derivation of the task hybrid hierarchy-based solution.

## 2. Preliminaries

From the rotational momentum conservation equation, the following expression can be obtained:

$$\boldsymbol{I}_{\rm S}\boldsymbol{w}_{\rm b} + \boldsymbol{I}_{\rm M}\dot{\boldsymbol{\theta}} = \boldsymbol{L}_0 \tag{1}$$

where $\dot{\boldsymbol{\theta}} \in \mathbf{R}^{n\times 1}$ is the angular velocity, $\boldsymbol{w}_{\rm b}$ is the angular velocities of the base, $\boldsymbol{I}_{\rm S} \in \mathbf{R}^{l\times l}$ is the rotation-related inertia matrix of the base, $\boldsymbol{I}_{\rm M} \in \mathbf{R}^{l\times n}$ is the coupling inertia-related matrix, and $\boldsymbol{L}_0$ is the initial momentum, $n$ is the dimension of the freedom of a manipulator, and $l$ is the dimension of the base-related task.

Furthermore, assuming that the dimension of the Cartesian space task is $m$, the end-effector can be expressed as

$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{\rm S}\boldsymbol{w}_{\rm b} + \boldsymbol{J}_{\rm M}\dot{\boldsymbol{\theta}} + \dot{\boldsymbol{x}}_0 \tag{2}$$

where $\dot{\boldsymbol{x}} \in \mathbf{R}^{m}$ is the end-effector velocity vector, and $\dot{\boldsymbol{x}}_0 \in \mathbf{R}^{m}$ is the initial rate vector of the end-effector. $\boldsymbol{J}_{\rm S} \in \mathbf{R}^{m\times 3}$ and $\boldsymbol{J}_{\rm M} \in \mathbf{R}^{m\times n}$ are the Jacobian matrices.

The non-minimum-norm solutions of Eq. (1), noted as $\dot{\boldsymbol{\theta}}_{\rm B\_NM}$, can be written in a general form as

$$\dot{\boldsymbol{\theta}}_{\rm B\_NM} = \boldsymbol{I}_{\rm M}^{+}(\boldsymbol{L}_0 - \boldsymbol{I}_{\rm S}\boldsymbol{w}_{\rm b}) + \boldsymbol{P}\dot{\boldsymbol{\zeta}} = \dot{\boldsymbol{\theta}}_0 + \boldsymbol{P}\dot{\boldsymbol{\zeta}} \tag{3}$$

where $\boldsymbol{P} = (\boldsymbol{I} - \boldsymbol{I}_{\rm M}^{+}\boldsymbol{I}_{\rm M})$, $\boldsymbol{I}$ denotes the identity matrix. $(\cdot)^{+}$ is the Moore–Penrose pseudoinverse. $\dot{\boldsymbol{\zeta}}$ is an arbitrary vector. $\dot{\boldsymbol{\theta}}_0 = \boldsymbol{I}_{\rm M}^{+}(\boldsymbol{L}_0 - \boldsymbol{I}_{\rm S}\boldsymbol{w}_{\rm b})$ is the specific solution of Eq. (1).

Let $\boldsymbol{N} = \{\dot{\boldsymbol{\theta}}_{\rm B\_NULL} : \dot{\boldsymbol{\theta}}_{\rm B\_NULL} = \boldsymbol{P}\dot{\boldsymbol{\zeta}}, \forall \dot{\boldsymbol{\zeta}}\}$, in which $\dot{\boldsymbol{\theta}}_{\rm B\_NULL}$ are the reactionless joint angular velocities. This reactionless kernel is well known as the RNS.Substituting Eq. (3) into Eq. (2) obtains

$$(\boldsymbol{J}_{\rm S} - \boldsymbol{J}_{\rm M}\boldsymbol{I}_{\rm M}^{+}\boldsymbol{I}_{\rm S})\boldsymbol{w}_{\rm b} + \boldsymbol{J}_{\rm M}\boldsymbol{P}\dot{\boldsymbol{\zeta}} = \dot{\boldsymbol{x}} - \dot{\tilde{\boldsymbol{x}}}_0 \tag{4}$$

where $\dot{\tilde{\boldsymbol{x}}} = \dot{\boldsymbol{x}}_0 + \boldsymbol{J}_{\rm M}\boldsymbol{I}_{\rm M}^{+}\boldsymbol{L}_0$. Eq. (4) can also be written as

$$\dot{\boldsymbol{\zeta}} = (\boldsymbol{J}_{\rm M}\boldsymbol{P})^{+}(\dot{\boldsymbol{x}} - \dot{\tilde{\boldsymbol{x}}}_0 - (\boldsymbol{J}_{\rm S} - \boldsymbol{J}_{\rm M}\boldsymbol{I}_{\rm M}^{+}\boldsymbol{I}_{\rm S})\boldsymbol{w}_{\rm b}) \tag{5}$$

Furthermore, substituting Eq. (5) into Eq. (3), we can obtain

$$\dot{\boldsymbol{\theta}} = \boldsymbol{I}_{\rm M}^{+}(\boldsymbol{L}_0 - \boldsymbol{I}_{\rm S}\boldsymbol{w}_{\rm b}) + (\boldsymbol{J}_{\rm M}\boldsymbol{P})^{+}(\dot{\boldsymbol{x}} - \dot{\tilde{\boldsymbol{x}}}_0 - (\boldsymbol{J}_{\rm S} - \boldsymbol{J}_{\rm M}\boldsymbol{I}_{\rm M}^{+}\boldsymbol{I}_{\rm S})\boldsymbol{w}_{\rm b}) \tag{6}$$

where $\boldsymbol{P}(\boldsymbol{H}\boldsymbol{P})^{+} = (\boldsymbol{H}\boldsymbol{P})^{+}$, as $\boldsymbol{P}$ being a symmetrical and idempotent projectional matrix.

Assume that $\boldsymbol{L}_0 = 0$ and $\dot{\boldsymbol{x}}_0 = 0$. From Eqs. (1) and (2), we can get the following equation:

$$\begin{bmatrix} \boldsymbol{w}_{\rm b} \\ \dot{\boldsymbol{x}} \end{bmatrix} = \begin{bmatrix} -\boldsymbol{I}_{\rm S}^{-1}\boldsymbol{I}_{\rm M} \\ \boldsymbol{J}_{\rm M} - \boldsymbol{J}_{\rm S}\boldsymbol{I}_{\rm S}^{-1}\boldsymbol{I}_{\rm M} \end{bmatrix}\dot{\boldsymbol{\theta}} = \boldsymbol{J}_{\rm E}\dot{\boldsymbol{\theta}} \tag{7}$$

where $\boldsymbol{J}_{\rm E}$ is the extended Jacobian.

Furthermore, $\dot{\boldsymbol{\theta}}$ can be obtained by the least-squares based solution as follows:

$$\dot{\boldsymbol{\theta}} = \boldsymbol{J}_{\rm E}^{*}\begin{bmatrix} \boldsymbol{w}_{\rm b} \\ \dot{\boldsymbol{x}} \end{bmatrix} \tag{8}$$

where $\boldsymbol{J}_{\rm E}^{*} = \boldsymbol{J}_{\rm E}^{-1}$, when $3 + m = n$ and $\boldsymbol{J}_{\rm E}^{*} = \boldsymbol{J}_{\rm E}^{-1}$, when $3 + m < n$, $(\boldsymbol{J}_{\rm E}^{*} \in \mathbf{R}^{n\times(3+m)})$. We call this the extended Jacobian (EJ)-based algorithm.



Please cite this article in press as: ZHOU C et al. Hybrid task priority-based motion control of a redundant free-floating space robot, *Chin J Aeronaut* (2017), http://dx.doi.org/10.1016/j.cja.2017.08.009