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Rotational-path decomposition based recursive planning for spacecraft attitude reorientation

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ABSTRACT

The spacecraft reorientation is a common task in many space missions. With multiple pointing constraints, it is greatly difficult to solve the constrained spacecraft reorientation planning problem. To deal with this problem, an efficient rotational-path decomposition based recursive planning (RDRP) method is proposed in this paper. The uniform pointing-constraint-ignored attitude rotation planning process is designed to solve all rotations without considering pointing constraints. Then the whole path is checked node by node. If any pointing constraint is violated, the nearest critical increment approach will be used to generate feasible alternative nodes in the process of rotational-path decomposition. As the planning path of each subdivision may still violate pointing constraints, multiple decomposition is needed and the reorientation planning is designed as a recursive manner. Simulation results demonstrate the effectiveness of the proposed method. The proposed method has been successfully applied in two SPARK microsatellites to solve onboard constrained attitude reorientation planning problem, which were developed by the Shanghai Engineering Center for Microsatellites and launched on 22 December 2016.

1. Introduction

Attitude reorientation is often required to accomplish specific missions for in-orbit spacecraft. However, the spacecraft attitude maneuver will be limited by various constraints [1,2]. For instance, some optical sensors (e.g. infrared telescopes and star sensors) cannot be exposed to bright celestial objects, otherwise they may be damaged. Normal operation of some instruments requires that the maneuver angular velocity should not be too large. Moreover, the control torque provided by actuators is bounded generally.

The constrained spacecraft reorientation problem has been studied previously. McInnes [3] used the artificial potential function, which applies high potential around forbidden zones, to avoid pointing constraints. This method mainly focuses on the user-imposed limits (e.g. pointing constraints), but the physical limits (e.g. control torque and angular velocity constraints) are not considered. Additionally, the Euler angle representation may lead to singularities. Hablani [4] defined exclusion regions on the unit sphere, and obtained ideal tangential exclusion path by solving two related slew angles, namely the required pitch/yaw angle and the exclusion angle of the bright object with respect to the slew plane. The geometric approach is mainly applicable to problems where only a small number of pointing constraints are present.

Frazzoli et al. [5,6] applied randomized path planning algorithm to solve the problem, which is capable of searching out admissible attitude maneuver path quickly. Kjellberg et al. [7,8] used the icosahedron discretization technique, and an admissible path satisfying pointing constraints was found with the A* pathfinding algorithm. In their planning algorithms, both Frazzoli and Kjellberg did not handle bounded constraints and dynamic constraints, which were considered in the process of attitude control.

Kim et al. [9,10] transformed the pointing constraints into convex quadratic constraints, and used the semidefinite programming method to obtain feasible attitude maneuver path. Tam et al. [2] extended Kim's work and used the mixed integer convex programming method to solve the constrained attitude maneuver problem.

Our research is devoted to the onboard rapid planning methods of the constrained spacecraft reorientation. Furthermore, we hope to provide support for China's deep space exploration project, such as Mars exploration and asteroid exploration. From the point of view of reliability, deterministic algorithms are preferred. As the onboard resources are limited, the computational cost should be specially addressed besides the satisfaction of multiple complex constraints.

This paper proposes an efficient rotational-path decomposition based recursive planning (RDRP) method to obtain a feasible constrained

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Abbreviations

BVN	Bounded-constraint-Violated Node
NCI	Nearest Critical Increment
PIARP	Pointing-constraint-Ignored Attitude Rotation Planning
PVN	Pointing-constraint-Violated Node
RDN	Rotational-path Decomposition Node
RDRP	Rotational-path Decomposition based Recursive Planning
RRT	Rapidly-exploring Random Tree

attitude maneuver solution. The uniform pointing-constraint-ignored attitude rotation planning (PIARP) process is designed to solve all rotations without considering pointing constraints. If any pointing constraint is violated, the nearest critical increment (NCI) approach will be used to generate feasible alternative nodes in the process of rotational-path decomposition. Different from previous geometric approach [4], the proposed method does not depend on careful selection of the intermediate nodes and thus the planning path of each subdivision may still violate pointing constraints. Hence, multiple decomposition is needed and the reorientation planning is designed as a recursive manner. The proposed RDRP method implies a general solving strategy or framework. Simulation results demonstrate the effectiveness of the proposed method. The proposed method has been successfully applied in two SPARK microsatellites to solve onboard constrained attitude reorientation planning problem, which were developed by the Shanghai Engineering Center for Microsatellites and launched on 22 December 2016.

2. Problem statement

The constrained spacecraft reorientation planning problem is to compute the profiles of the spacecraft attitude, angular velocity, and control torque, which should satisfy boundary conditions, pointing constraints, bounded constraints, and attitude dynamic and kinematic constraints. The attitude kinematic equation [11,12] of the rigid spacecraft can be expressed using the unit-quaternion.

$$\dot{\mathbf{q}} = \frac{1}{2}\mathbf{Q}\boldsymbol{\omega} \tag{1}$$

where $\boldsymbol{q} = [q_0, q_1, q_2, q_3]^{\mathrm{T}} \in \mathbb{R}^4$ denotes the unit-quaternion that represents the attitude of the spacecraft in the body frame relative to the inertial frame. The quaternion needs to satisfy the normalization constraint $\|\boldsymbol{q}\|_2 = 1$. q_0 is the scalar part of the quaternion. $[\cdot]^{\mathrm{T}}$ represents the vector transposition. $\|\cdot\|_2$ represents the 2-norm of the vector. $\boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3]^{\mathrm{T}} \in \mathbb{R}^3$ is the angular velocity (relative to the inertial frame) of the spacecraft in the body frame. Additionally,

$$\mathbf{Q} = \begin{bmatrix} -q_1 & -q_2 & -q_3 \\ q_0 & -q_3 & q_2 \\ q_3 & q_0 & -q_1 \\ -q_2 & q_1 & q_0 \end{bmatrix} \tag{2}$$

The angular velocity expressed by the unit-quaternion and its derivative can be obtained from Eq. (1) according to [13,14].

$$\boldsymbol{\omega} = 2\mathbf{W}\dot{\mathbf{q}} \tag{3}$$

where

$$\mathbf{W} = \begin{bmatrix} -q_1 & q_0 & q_3 & -q_2 \\ -q_2 & -q_3 & q_0 & q_1 \\ -q_3 & q_2 & -q_1 & q_0 \end{bmatrix} \tag{4}$$

The attitude dynamic equation [11,12] of the rigid spacecraft can be represented as follows:

$$\mathbf{J}\dot{\boldsymbol{\omega}} = u - \boldsymbol{\omega} \times (\mathbf{J}\boldsymbol{\omega}) \tag{5}$$

where $\mathbf{u} = [u_1, u_2, u_3]^{\mathrm{T}}$ is the control torque in the body frame. $\boldsymbol{J}$ is the inertia matrix of the spacecraft. $\times$ represents the vector cross product. The control torque expressed by the angular velocity and its derivative [15,16] can be obtained from Eq. (5).

$$\boldsymbol{u} = \mathbf{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times (\mathbf{J}\boldsymbol{\omega}) \tag{6}$$

In the process of the spacecraft attitude maneuver, the lights of bright celestial objects (e.g. the sun) cannot enter into the field of view of certain optical sensors (e.g. infrared telescopes and star sensors). That is, the angle between the boresight vector of the sensor and the direction vector of the bright celestial object should not be less than the corresponding pointing constraint angle, as shown in Fig. 1.

The pointing constraint above can be expressed in the form of inequality [17,18].

$$\boldsymbol{r}_B^{\mathrm{T}}(\boldsymbol{C}_{BI}\boldsymbol{r}_I) \le \cos\theta \tag{7}$$

where $\boldsymbol{r}_B = [r_{B_1}, r_{B_2}, r_{B_3}]^T$ represents the unit direction vector of the sensor in the body frame. $\boldsymbol{r}_I = [r_{I_1}, r_{I_2}, r_{I_3}]^{\mathrm{T}}$ represents the unit direction vector from the spacecraft to the bright celestial object in the inertial frame. $\boldsymbol{C}_{BI}$ denotes the attitude rotation matrix from the inertial frame to the body frame. θ is the pointing constraint angle.

$$\boldsymbol{C}_{BI} = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2q_1q_2 + 2q_3q_0 & 2q_1q_3 - 2q_2q_0 \\ 2q_1q_2 - 2q_3q_0 & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2q_2q_3 + 2q_1q_0 \\ 2q_1q_3 + 2q_2q_0 & 2q_2q_3 - 2q_1q_0 & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix} \tag{8}$$

During the spacecraft attitude maneuver, control torque provided by actuators is bounded. Moreover, the measuring instruments have limited measuring range. Some instruments may need mild angular velocity for their normal operation. Thus, the angular velocity of the spacecraft is also required to be limited within a certain range. The two bounded constraints can be expressed as the following inequalities respectively [11,12].

$$|u_i| \le u_{\max},\ i = 1, 2, 3 \tag{9}$$

$$|\omega_i| \le \omega_{\max},\ i = 1, 2, 3 \tag{10}$$

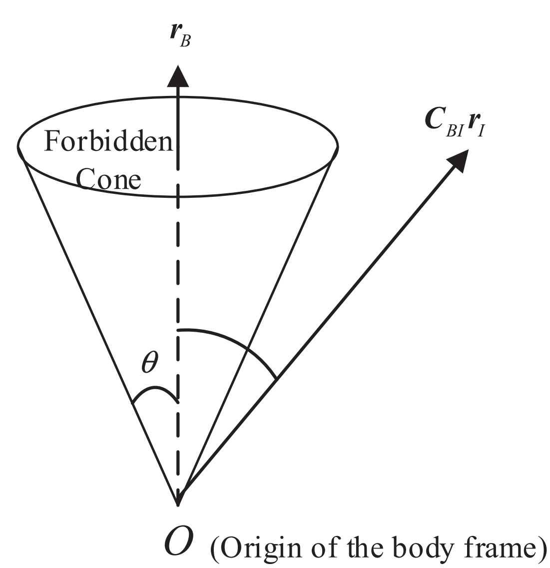

Fig. 1. Schematic diagram of the pointing constraint.