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Time-optimal spacecraft attitude maneuver path planning under boundary and pointing constraints

Changqing Wu[a,b], Rui Xu[a,b,*], Shengying Zhu[a,b], Pingyuan Cui[a,b]

[a] School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China
[b] Key Laboratory of Autonomous Navigation and Control for Deep Space Exploration, Ministry of Industry and Information Technology, Beijing 100081, China

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ABSTRACT

The rapid large angle attitude maneuver capability of spacecraft is required during many space missions. This paper addresses the challenge of time-optimal spacecraft attitude maneuver under boundary and pointing constraints. From the perspective of the optimal time, the constrained attitude maneuver problem is summarized as an optimum path-planning problem. To address this problem, a metaheuristic maneuver path planning method is proposed, Angular velocity-Time Coding Differential Evolution (ATDE). In the ATDE method, the angular velocity and time are coded for attitude maneuver modeling, which increases the number of variables and results in a high-dimensional problem. In order to deal with this problem, differential evolution is employed to perform variation and evolution. The boundary and pointing constraints are constructed into the fitness function for path evaluation. Finally, numerical simulations for the different cases were performed to validate the feasibility and effectiveness of the proposed method.

1. Introduction

With the continued development of space missions, the requirement for rapid large angle attitude maneuver capability is urgent [1,2], especially for disaster warning, scientific exploration, military applications, and other tasks. The Guidance, Navigation, and Control (GNC) system of a spacecraft is required to provide appropriate control torque, allowing the spacecraft to move from its current attitude to a new attitude in the possible shortest time [3].

For spacecraft attitude maneuver, the light of bright celestial bodies (such as the sun) should be prevented from entering the view field of certain optical sensors (such as an infrared sensor or low-light sensitive elements), as this could lead to temporary blindness or damage of the optical sensors. During maneuvering, the process direction vector of the solar array must be maintained within certain requirements to continuously provide electric energy supply. These directional constraints greatly limit the feasible region of spacecraft attitude maneuver [4]. Additionally, the limit of the angular velocity and control torque will also affect the attitude maneuver path [5]. Due to these complex constraints, the planning of a time-optimal maneuver path can be very challenging for a spacecraft GNC system.

The constrained attitude maneuver problem has been studied previously. McInnes et al. [6,7] introduced the pointing constraint into the structure of the potential function, and obtained the control input expression by application of the second differentiable method of Lyapunov. This method required less calculation resources, but utilized the Euler angle to represent kinematic and dynamic constraints, which is vulnerable to a singular point. Additionally, the limit of the angular velocity and control torque and meaningful attitude maneuver performance indicators (time, energy, etc.) were not considered in these studies. Frazzoli [8] used stochastic programming theory to facilitate the planning method of an attitude maneuver path, with a focus on the efficiency of the algorithm. On this basis, Zhong [9] mapped attitude-pointing constraints to the Rodrigues space to improve planning speed. However, there was no consideration of attitude dynamics, and this method requires modification before practical application. Kim [10] used a semi-definite programming method to complete a single-step plan, that required control input torque of current time. A single-step control mode can easily violate the constraints due to limited torque control.

It is difficult to realize a time-optimal spacecraft attitude maneuver under complex constraints because the solutions are related to complex nonlinear problems. The analytical solutions are difficult to obtain by indirect methods. Melton [11] provided a suboptimal solution using a numerical method from the perspective of optimal control. Although the theoretical interest in such an approach is evident, it is very computa-

* Corresponding author at: School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China.
E-mail address: xurui@bit.edu.cn (R. Xu).

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tionally intensive and may not be generalizable for rest-to-rest motions in obstacle-free environments. Spiller et al. [12] employed a metaheuristic approach and a method based on the evolution of kinematics and the successive obtainment of the control law was presented as inverse dynamics particle swarm optimization. Ultimately, a near-optimal solution was obtained, which fully satisfies all the pointing constraints and boundaries.

This paper was inspired by this work of Spiller et al. The boundary constraints and pointing constraints are separately described and analyzed in detail. The pointing constraints were translated to quadratic form to simplify the representation and computation in the state space of attitude. From the perspective of optimal time, the constrained attitude maneuver problem is summarized as an optimum path-planning problem. On the basis of a metaheuristic approach, a novel attitude maneuver path planning method called Angular velocity-Time Coding Differential Evolution (ATDE) is proposed here to obtain the maneuver path. In the ATDE method, the angular velocity and time are coded for attitude maneuver modeling, which increases the number of variables resulting in a high-dimensional problem. To deal with this problem, a differential evolution approach was employed for variation and evolution [13,14]. The boundary and pointing constraints were constructed into the fitness function for path evaluation. Finally, numerical simulations for the different cases were performed to validate the feasibility and effectiveness of the proposed method.

2. Attitude constraints of spacecraft

It is essential to describe and analyze the attitude constraints of the spacecraft during attitude maneuvering in detail. In this section, the constraints of kinematic, dynamics, boundary and attitude-pointing are described. In particular, the attitude-pointing constraints (including forbidden and mandatory constraints) are translated to quadratic form to simplify the representation and computation in attitude quaternion space.

2.1. Attitude kinematic and dynamic constraints

To avoid singularity, the unit quaternion representation is utilized to parameterize maneuvering. So for the rigid spacecraft, the attitude dynamic and kinematic constraints are expressed as follows [15,16] :

$$\mathbf{J}\dot{\boldsymbol{\omega}} = \boldsymbol{u} - \boldsymbol{\omega}^{\times}\mathbf{J}\boldsymbol{\omega} \tag{1}$$

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

where $\boldsymbol{q} = [q_0, q_1, q_2, q_3]^{\mathrm{T}}$ is the unit quaternion representing the attitude of the rigid body, which is a rotation from the body frame to inertial frame and must satisfy the normalization constraint $\|\boldsymbol{q}\|_2 = 1.\|\bullet\|_2$ represents the 2−norm. $\boldsymbol{\omega} = [\omega_1, \omega_2, \omega_3]^{\mathrm{T}}$ is the angular velocity. Additionally,

$$\mathbf{Q} = \begin{bmatrix} -q_1 & -q_2 & -q_3 \\ q_0 & -q_3 & q_2 \\ q_3 & q_0 & -q_1 \\ -q_2 & q_1 & q_0 \end{bmatrix}, \boldsymbol{\Omega} = \begin{bmatrix} 0 & -\omega_1 & -\omega_2 & -\omega_3 \\ \omega_1 & 0 & \omega_3 & -\omega_2 \\ \omega_2 & -\omega_3 & 0 & \omega_1 \\ \omega_3 & \omega_2 & -\omega_1 & 0 \end{bmatrix} \tag{3}$$

$\boldsymbol{J}$ is the moment of inertia, $\boldsymbol{J} = diag(J_1, J_2, J_3)$. $\boldsymbol{u}$ is the control torque, $\boldsymbol{u} = [u_1, u_2, u_3]^{\mathrm{T}}$. $\boldsymbol{\omega}^{\times}$ is the cross-product matrix of angular velocity $\boldsymbol{\omega}$:

$$\boldsymbol{\omega}^{\times} = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \tag{4}$$

2.2. Boundary constraints

During implementation, the control torque is bounded and must satisfy the following constraint:

$$|u_i| \le \gamma_T i = 1, 2, 3 \tag{5}$$

During an attitude maneuver, some sensors require mild angular velocity for conducting normal work. Thus, the angular velocity needs to be limited within a certain range and satisfy the following constraint:

$$|\omega_i| \le \gamma_\omega i = 1, 2, 3 \tag{6}$$

2.3. Attitude-pointing constraints

Attitude-pointing constraints depend on the external environment of the spacecraft, which decreases the potential region of attitude space. Once the constraints are exceeded, some payload of the spacecraft will be damaged, thereby affecting the mission. So the analysis of pointing constraints is a basic program. Overall, attitude-pointing constraints can be divided into two categories——forbidden constraints and mandatory constraints [17].

2.3.1. Forbidden constraint

Spacecraft often have some sensitive instruments, which will be used to perform space tasks. It is essential to avoid bright celestial objects in the field of view of the perception sensors. In mathematical terms, the vector angle between the sensitive instruments and the sun should be greater than the field of view of the sensitive instruments. This constraint is considered a forbidden constraint.

As shown in Fig. 1, $\boldsymbol{r}_B$ represents the direction vector of the sensitive instrument in the body coordinate system. θ is the field of view of the sensitive instrument. $\boldsymbol{r}_I$ is the direction vector of a bright celestial object (e.g., the sun) in an inertial coordinate system. The angle between $\boldsymbol{r}_I$ and $\boldsymbol{r}_B$ should be greater than θ. This forbidden constraint can be expressed in the form of Eq. (7).

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

where $\boldsymbol{r}_B = [r_{B_1} \ r_{B_2} \ r_{B_3}]^{\mathrm{T}}$, $\boldsymbol{r}_I = [r_1 \ r_2 \ r_3]^{\mathrm{T}}$, $\boldsymbol{C}_{BI}$ represents the spacecraft attitude cosine matrix from the inertial coordinate system to the body coordinate system. Considering the relative motion between the spacecraft and the sun:

$$\boldsymbol{C}_{BI}\boldsymbol{r}_I = \boldsymbol{r}_I - 2\underline{\boldsymbol{q}}^{\mathrm{T}}\underline{\boldsymbol{q}}\boldsymbol{r}_I + 2\underline{\boldsymbol{q}}\,\underline{\boldsymbol{q}}^{\mathrm{T}}\boldsymbol{r}_I + 2q_0(\boldsymbol{r}_I^{\times}\underline{\boldsymbol{q}}) \tag{8}$$

where $\underline{\boldsymbol{q}}$ is the vector part of quaternion and $\underline{\boldsymbol{q}} = [q_1, q_2, q_3]^{\mathrm{T}}$, $\boldsymbol{r}_I^{\times}$ is the cross product matrix of $\boldsymbol{r}_I$.

We can turn the Eq. (7) into a more compact form and provide the Eq. (9) in the form of quadratic constraints [16].

$$\boldsymbol{q}^{\mathrm{T}}\boldsymbol{K}_f\boldsymbol{q} \le 0 \tag{9}$$

Where,

$$\boldsymbol{K}_f = \begin{bmatrix} \boldsymbol{r}_I^{\mathrm{T}}\boldsymbol{r}_B - \cos\theta & (\boldsymbol{r}_B^{\times}\boldsymbol{r}_I^{\mathrm{T}})^{\mathrm{T}} \\ \boldsymbol{r}_B^{\times}\boldsymbol{r}_I^{\mathrm{T}} & \boldsymbol{r}_I\boldsymbol{r}_B^{\mathrm{T}} + \boldsymbol{r}_B\boldsymbol{r}_I^{\mathrm{T}} - (\boldsymbol{r}_I^{\mathrm{T}}\boldsymbol{r}_B + \cos\theta)\mathbf{I}_3 \end{bmatrix} \tag{10}$$

where $\boldsymbol{r}_B^{\times}$ is the cross-product matrix of $\boldsymbol{r}_B$.

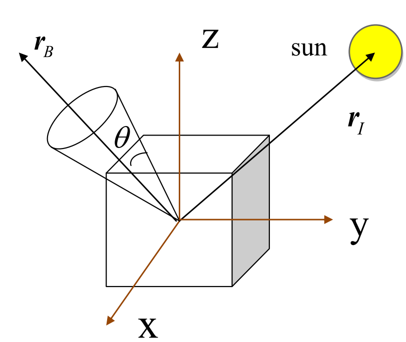

Fig. 1. Schematic of forbidden constraint.