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Three-Axis Attitude Maneuver of Spacecraft by Reaction Wheels with Rotation Speed Constraints

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Abstract: Conventionally, spacecraft control their total angular momentum with magnetic torquers or thrusters. However, for a micro interplanetary spacecraft such as PROCYON (Funase et al. 2014), magnetic torquers cannot be used when it is far from the earth and thrusters also cannot be used frequently because of limited fuel storage. In that case, the attitude should be controlled using reaction wheels and the total angular momentum is fixed in the inertial frame. The problem is that when the total angular momentum is large, the wheels are required to store large angular momenta, which, in some attitude conditions, exceed the capacity of the reaction wheels. In order to perform three-axis attitude maneuver using sun sensors and gyroscopes as sensors and reaction wheels as actuators even with a large total angular momentum, the proposed control method applies pointing control of the angular momentum and that of the sun direction in sequence. The results show that the success rate of a three-axis maneuver from a certain attitude to another within one hour using the proposed method is 99.9% on average, even when the spacecraft has a large total angular momentum, while that of the conventional method is 48.3% on average.

Keywords: Interplanetary Spacecraft, Attitude Control, Reaction Wheels, Rotation Speed Constraints

1. INTRODUCTION

1.1 Background

In 2014, the first micro interplanetary spacecraft, PROCYON (Funase et al. 2014) was launched and later achieved its primary mission (Funase et al. 2015). Also, in 2016, NASA announced that in 2018, the Space Launch System will carry into deep space 13 CubeSats such as NEA Scout (McNutt et al. 2014). With technology more and more advanced, it can be predicted that the number of micro interplanetary spacecraft will dramatically increase in the near future.

These interplanetary spacecraft cannot use magnetic torquers because they are outside the Earth's magnetic field. They also cannot use the thrusters frequently due to the limited fuel storage. Therefore, they usually use the reaction wheels in order to attain attitude maneuvers and the total angular momentum of the spacecraft is thus fixed in the inertial frame during the maneuver.

The direction of the total angular momentum of the spacecraft, which is fixed in the inertial frame, in the body frame depends on the attitude. On the other hand, the maximum magnitude of the angular momentum that the reaction wheels can store differs according to the direction. Therefore, whether the reaction wheels can store the total angular momentum of the spacecraft depends on the attitude. In other words, if the magnitude of the total angular momentum is relatively large compared to the maximum angular momentum storage of the reaction wheels, the attitude that the spacecraft can realize is limited.

This is a problem because when the realizable attitude is limited, it is necessary to ensure that in each state during the maneuver, the reaction wheels can store the angular momentum as required. The conventional three-axis attitude maneuver algorithm, which usually does not take into account the wheels' capacity, may not succeed.

An example of the situations in which this problem is critical is when a micro interplanetary spacecraft executes the sun pointing maneuver in order to ensure the solar power generation shortly after it is separated from the rocket and detumble itself. Since a micro spacecraft is launched as a secondary payload in most cases, the angular momentum is not well controlled during the separation from the rocket. This results in the large total angular momentum during the sun pointing maneuver.

1.2 Proposed Method

The most common method for three-axis attitude maneuver of spacecraft is to calculate the error rotation between the current attitude and the target attitude and to derive the control torque using PID control method. In the proposed method, which is discussed in detail in section 2, the control angular velocity is derived instead in order to clarify the amount of angular momentum the reaction wheels need to store and to make it easier to avoid their saturation.

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Furthermore, the proposed method splits the three-axis attitude maneuver into two pointing maneuvers, one with the total angular momentum vector and the other with the sun direction vector. As discussed in section 3, this makes it possible to easily avoid the wheels' saturation while ensuring the proper control is executed with little effect from the saturation avoidance.

2. PROBLEM DEFINITION

2.1 Assumptions

- The total angular momentum is a nonzero vector.
- The total angular momentum is fixed in the inertial frame.
- Sun sensors and gyroscopes are used as sensors.
- Reaction wheels with limited angular momentum capacity are used as actuators.

2.2 Objectives

- To attain three-axis maneuver from a certain stabilized attitude to another.
- To maximize the success rate of the maneuver within a certain period of time.

2.3 Factors to be considered

- The total angular momentum is so large that it cannot be stored by the reaction wheels in some attitude conditions.
- Therefore, it should be assured that the angular momentum of the wheels during the maneuver should be within the wheels' capacity.

3. PROPOSED CONTROL ALGORITHM

3.1 Attitude Dynamics

The dynamics equations of the spacecraft and the reaction wheels in the body coordinate are given as

$$\dot{\boldsymbol{\omega}} = I^{-1}\{-\boldsymbol{\omega} \times (I\boldsymbol{\omega} + \boldsymbol{h}) + \boldsymbol{u}_{ext} + \boldsymbol{u}\}, \quad (1)$$

$$\dot{\boldsymbol{h}} = -\boldsymbol{u}, \quad (2)$$

where I is the spacecraft's inertia matrix, $\boldsymbol{\omega}$ is the angular velocity of the spacecraft, $\boldsymbol{u}_{ext}$ is the external torque acting on the spacecraft, $\boldsymbol{u}$ is the reaction wheels' torque acting on the spacecraft, and $\boldsymbol{h}$ is the total angular momentum of the wheels (Bang et al. 2003). For this problem, the external torque disturbance such as solar radiation pressure torque is negligible, i.e., $\boldsymbol{u}_{ext} = \boldsymbol{0}$ because the maneuver is executed within a sufficiently short period of time.

3.2 Rotation Speed Constraints of the Reaction Wheels

Let us consider a spacecraft with n reaction wheels, the i-th of which has the rotation axis of unit vector $\boldsymbol{w}_i$, the moment of inertia around the axis of I_{wi}, and the maximum rotation speed of $\omega_{wi,max}$. Then h_{wi}, the magnitude of the angular momentum of the i-th reaction wheel, is subject to the constraint represented as

$$-h_{wi,max} \le h_{wi} \le h_{wi,max} \quad (3)$$

where $h_{wi,max} = I_{wi}\omega_{wi,max}$ is the magnitude of the maximum angular momentum storage of the i-th reaction wheel.

The total angular momentum of the reaction wheels, can be denoted as the sum of the angular momentum of each wheel, that is,

$$\boldsymbol{h} = \sum_{i=1}^{n} h_{wi}\boldsymbol{w}_i = W\boldsymbol{h}_w \quad (4)$$

where

$$W := [\boldsymbol{w}_1 \quad \cdots \quad \boldsymbol{w}_n], \quad (5)$$

$$\boldsymbol{h}_w := [h_{w1} \quad \cdots \quad h_{wn}]. \quad (6)$$

It is known that the domain of $\boldsymbol{h}$ subject to (3) is a polyhedron (Reynolds & Markley 2001).

3.3 Two Pointing Controls

The objective of pointing control is to realize the attitude of the spacecraft where the vector of interest, which is fixed in the inertial frame, is in the target direction in the body-fixed coordinate. Therefore, with only one pointing control, the final attitude has one degree of freedom in the angle around the target direction vector. In the proposed method, we apply two pointing controls in order to attain three-axis attitude maneuver. We adopt as the vectors of interest the sun direction vector and the total angular momentum vector of the spacecraft, both of which can be regarded as fixed in the inertial frame.

The two pointing controls are applied in sequence. First, the control of the angular momentum vector is applied and the target attitude is realized except the one degree of freedom in the angle around the target vector. Then the control of the sun vector is added in order to attain the three-axis attitude maneuver.

$\boldsymbol{\omega}$, the angular velocity of the spacecraft, can be measured with the gyroscopes and $\boldsymbol{L}^b$, the total angular momentum vector in the body frame, can be calculated as

$$\boldsymbol{L}^b = I\boldsymbol{\omega} + \boldsymbol{h}. \quad (7)$$

Also, $\boldsymbol{e}_s^b$, the sun direction vector in the body frame, can be measured with the sun sensors.

When the coordinate transformation matrix from the body frame of the current attitude to that of the target attitude is C_{cur}^{tar}, $\boldsymbol{L}_{tar}^b$, the target vector for $\boldsymbol{L}^b$, and $\boldsymbol{e}_{sun,tar}^b$, the target vector for $\boldsymbol{e}_{sun}^b$, can be calculated as

$$\boldsymbol{L}_{tar}^b = C_{cur}^{tar}\boldsymbol{L}^b \quad (8)$$

$$\boldsymbol{e}_{sun,tar}^b = C_{cur}^{tar}\boldsymbol{L}^b \quad (9)$$