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Feedback slew algorithms for prolate spinners using Single–Thruster

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ABSTRACT

A number of low-cost open-loop slew control algorithms have been developed for prolate spinning spacecraft using single-thruster actuation. Robustness analysis indicates that these algorithms have high sensitiveness over thruster firing time error, spacecraft inertia error, and especially spin rate perturbations. This paper proposed two novel feedback slew algorithms, Feedback Half-Cone and Feedback Sector-Arc Slew, built on the existing open-loop algorithms and they use attitude and angular velocity feedback to compensate the errors in knowledge of spin rate, without external torques. As presented, after the first thruster actuation initiate the spin-axis precession, the feedback slew algorithms take attitude and spin-rate feedback to estimate the angular momentum and predict the spin-axis attitude during the slew. These techniques contribute to improve the cancelation thrust impulse accuracy and reduce the final nutation error. Simulations for a Penetrator mission scenario validate these feedback algorithms and show their slew performance and robustness over the perturbations mentioned above. It is proved that the attitude feedback greatly improves the slew accuracy and robustness.

1. Introduction

The attitude control algorithms proposed in this paper are discussed for Penetrator mission concept: a cylindrical missile-shaped projectile spinning around its minor axis of inertia performs a 90° spin axis reorientation manoeuvre to impact with a celestial body, burying itself into the subsurface for investigation. Japanese mission Lunar-A [1] and British MoonLITE mission [2] using above Penetrator concept both aimed to study the lunar subsurface. Spin stabilization is usually taken as it is a relatively low-cost means of stabilization. With only one thruster mounted perpendicular to the spin-axis, the attitude slew can be achieved using state-of-the-art single-thruster slew algorithms. Existing researches [3–6] on the prolate spinning spacecraft attitude manoeuvre have developed a series of slew algorithms using single-thruster in two categories: Half-cone derived algorithms and Pulse-train algorithms. Half-cone derived algorithms consist of Half-Cone (HC), Multi Half-Cone (MHC), Dual Half-Cone (DHC), Extended Half-Cone (EHC), Sector Arc Slew (SAS), Multi Sector Arc (MSA) slew, using the precession behaviour of a spinning prolate spacecraft. Pulse-train algorithms consist of Rhumb Line (RL) and Spin-Synch (SS) algorithms, which use a train of uniform torque pulses to achieve the attitude manoeuvre. The timing between two torque pulses is roughly (for Rhumb Line) or exactly (for Spin-Synch) equal to the spin period. Pulse-train algorithms can also be used for oblate spacecraft. Based on the Half-Cone slew using single-thruster, similar Half-Cone slew method using single-magnetorquer [7] are also developed aimed to apply on STRaND-1 [8] mission.

Previous analysis [3] concluded that within the range of manoeuvre angles the mission required, SAS, MSA, DC and EHC slews can achieve accurate slews. However above Half-Cone derived algorithms are all open-loop control without attitude feedback and the robustness analysis [9] indicates that they all show high sensitiveness over thruster firing time error, spacecraft inertia error, and especially spin rate perturbations. With about 1% of the spin-rate perturbation, the slew error would exceed over 50°, which can be treated as the failure of the manoeuvre. In order to improve the robustness of single-thruster slews, research is motivated to use attitude and angular velocity feedbacks to develop novel feedback slew algorithms. Feedback Half-Cone slew and Feedback Sector-Arc Slew are proposed in this paper based on the open-loop HC and SAS slews. For these two novel algorithms, angular momentum estimation and latter spin-axis attitude prediction are the key techniques and the adjusted timing of precession cancellation impulse in the last revolution of the manoeuvre contributes to a better slew accuracy.

Based on the numerical simulation for a given Penetrator mission scenario, thorough comparative analysis of the novel feedback algorithms and their corresponding open-loop algorithms is given focusing on spin-axis slew accuracy, slew duration and energy consumption.

The rest of this paper is organized as follows. Section 2. defines the coordinate frames of this research and Section 3. briefly presents the

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existing open-loop HC and SAS slew algorithms. Section 4. introduces the novel feedback HC and Feedback SAS slew algorithms as well as the techniques of angular momentum estimation and latter spin-axis attitude prediction using attitude feedback. Section 5. presents the slew performance and robustness analysis of the feedback algorithms compared with their corresponding open-loop ones, and the thorough comparison between these two feedback slews, which indicates a possible methodology to choose slew algorithms for a certain space mission for space engineers. In the end, Section 6. summarizes the conclusions of the paper.

2. Mathematical background

The fundamental mathematical background of the spinners' spin axis attitude manoeuvre is the rigid body rotational Kinematics and Dynamics. For a rigid body, the rotational movement driven by a torque applied on it is defined as Euler's Moment Equation, explained and demonstrated in Wertz [10]'s equation:

$$\boldsymbol{T} = \dot{\boldsymbol{H}}_{RI} = \dot{\boldsymbol{H}}_{SFB} + \boldsymbol{\omega} \times \boldsymbol{H} \tag{1}$$

For a prolate axisymmetric spinner, the angular velocity vector $\boldsymbol{\omega}$, spin axis Z and angular momentum vector $\boldsymbol{H}$ are in the same plane and this plane rotates about $\boldsymbol{H}$ with angular velocity ω_H. In external torque free case, the magnitudes and the relative positions of these vectors are constant during the rotation. λ is the inertia ratio which equals to I_Z/I_t. For a prolate spinner$0 < \lambda < 1$, and the relationships between these vectors are illustrated in Fig. 1. In Fig. 1, $\boldsymbol{\omega}$ can be geometrically decomposed in two sets of components:

(1) $\boldsymbol{\omega}_Z$ and $\boldsymbol{\omega}_{XY}$, which are perpendicular decompositions in SFB frame Z axis and XOY plane.
(2) $\boldsymbol{\omega}_N$ and $\boldsymbol{\omega}_H$, which are the non-perpendicular decompositions in Z axis and $\boldsymbol{H}$ vector direction, with an enclosed angle θdefined as the nutation angle.

This plane as well as Z axis and $\boldsymbol{\omega}$ rotates around the angular momentum $\boldsymbol{H}$ with angular velocity $\boldsymbol{\omega}_H$, namely inertial nutation rate. The body nutation rate $\boldsymbol{\omega}_N$ is the rotation rate of any point fixed in the spacecraft around Z axis relative to the orientation of $\boldsymbol{H}$. In inertial space, $\boldsymbol{\omega}$ rotates around $\boldsymbol{H}$ on a cone called the space cone. Similarly, $\boldsymbol{\omega}$ rotates around Z on a cone called the body cone. In total, the motion of the spacecraft is visualized as the body cone rolling on the space cone without slipping.

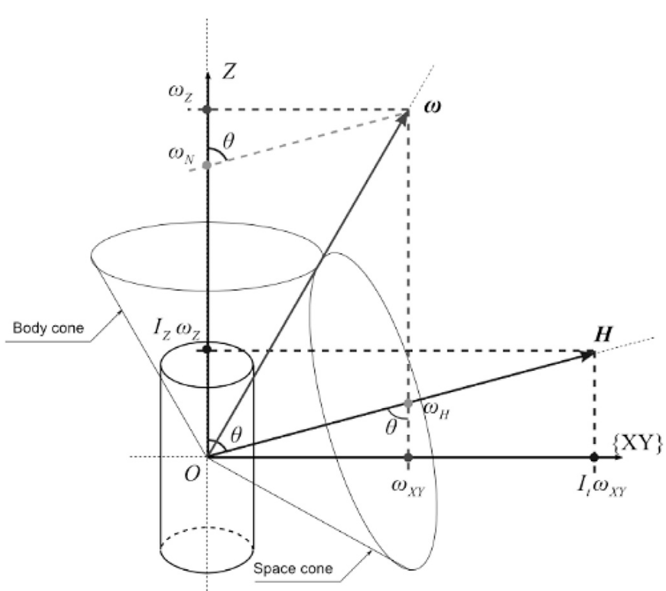

Fig. 1. Precession in Z-H plane illustration.

The relationship between ω_H, ω_N and $\omega_Z$can be derived as follows:

$$\omega_H = \frac{\boldsymbol{H}\omega_{XY}}{I_t\omega_{XY}} = \frac{\boldsymbol{H}}{I_t} = \frac{I_Z\omega_Z}{\cos(\theta)I_t} = \frac{\lambda\omega_Z}{\cos(\theta)} \tag{2}$$

$$\tan(\theta) = \frac{\omega_{XY}}{\omega_Z - \omega_N} = \frac{I_t\omega_{XY}}{I_Z\omega_Z} \Leftrightarrow$$

$$\omega_Z - \omega_N = \omega_{XY}\frac{I_Z\omega_Z}{I_t\omega_{XY}} = \lambda\omega_Z \Leftrightarrow$$

$$\omega_N = (1-\lambda)\omega_Z \tag{3}$$

where I_t and I_Z are the inertia around X/Y axis and around Z axis respectively.

3. State-of-the-art open-loop half-cone and Sector-Arc Slew algorithms

3.1. Half-Cone slew

For Half-Cone Slew, it is assumed that the prolate spacecraft is initially in a pure spin around SFB Z-axis. The thruster position and thrust direction are chosen to generate positive torque around SFB Y-axis. For example, the thruster could be mounted on the negative Z-axis with thrust vector pointing parallel to the negative X-axis. There is also an 'impulsive shot' assumption for simplicity that the thruster firing duration t_{on} is much smaller than the spin period. The Half-Cone method takes the following sequence of events (also illustrated in Fig. 2) where Z_0 and Z_t are the initial and target spin-axes:

(1) For $t < t_1$, the spacecraft is in a pure spinning around its Z_0-axis with no nutation.
(2) At $t = t_1$ the spacecraft X-axis is perpendicular to the $Z_0 - Z_t$ plane and the thruster generates an angular impulse in positive Y direction pointing to Z_t axis which drives the angular momentum vector away from Z_0-axis to half the $Z_0 - Z_t$ angle.
(3) For $t > t_1$, the spacecraft spin axis starts a precession motion around the intermediate $\boldsymbol{H}$ vector with no torques applied.

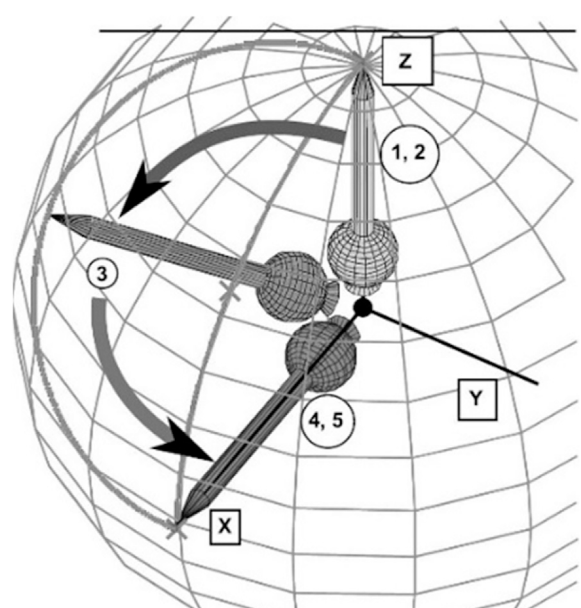

Fig. 2. The sequence of events for the Half-Cone Slew control manoeuvre [3].