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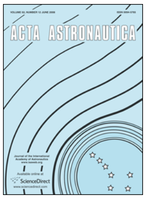

Detumbling of a rigid spacecraft via torque wheel assisted gyroscopic motion

Yiing-Yuh Lin*, Chin-Tzuo Wang

Department of Aeronautics and Astronautics, National Cheng Kung University, Tainan 70101, Taiwan, ROC

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ABSTRACT

A time and energy efficient two-part method for detumbling a rigid spacecraft using an onboard torque wheel and a set of three-axis magnetic torquer is presented in this paper. Part-1 of the method manipulates the speed of the wheel, whose spin axis is parallel to a designated body axis of a tumbling spacecraft, and induces a desired gyroscopic-like motion to align the designated axis with its total angular momentum, $\vec{H}_T$. The procedure in effect detumbles the spacecraft to rotate about the designated axis and distributes $\vec{H}_T$, which is conserved during this control period, between the body and the wheel. After the alignment is achieved, Part-2 control, activated with a specified momentum transfer parameter, η, can either quickly stop the body rotation by transferring its angular momentum to the wheel or offload most of the momentum into space, using the wheel and the magnetic torquer. Convergence criteria and control laws for both parts are derived from the Lyapunov stability analysis and the method of feedback linearization. The wheel performs as a momentum storing and transferring device regulating the angular momentum between the wheel and the body. It can also provide gyroscopic stiffness to stabilize the system while the magnetic torquer is offloading the momentum. Simulation results from the included cases indicate that significantly fast detumbling of the spacecraft can be achieved with Part-1 of the proposed method. The results also show that, under the same condition, either by transferring almost all $\vec{H}_T$ to the wheel or dumping it, the two-part method, with a chosen η and final residual momentum condition, requires much less time and energy needed than the B-dot method does. Moreover, the stability nature of the two-part method is heuristically substantiated as the wheel torques and the dipole moment were constrained in the simulation.

1. Introduction

When a spacecraft is deployed from the last stage of a launcher into orbit, it is released with a spin, which usually results in tumbling [1]. Also, it has become a trend in recent years to bundle several smaller satellites and eject them from a launcher in a single trip [2]. Notably, the Vegas, a new launcher of Arianespace for light-weight lifting purpose, had its successful test and maiden flight on 13 February 2012 [3]. At the critical moment after separation, the solar panels are not in place and the on-board electric power from the battery is limited but the spacecraft needs to use the magnetic torquer to perform despin control and sometimes subsequent attitude acquisition [4,5]. Safety considerations may require enough spin rate to make the course steady when the satellites are exiting from the launcher to prevent any collision with the launcher or among themselves. The need for an effective method to detumble these satellites is evident [6,7].

The simple B-dot control method [8–10] has been commonly used on spacecraft either in the detumbling mode following deployment or in the safety mode after a

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* Corresponding author. Tel.: +886 62757575/63673.
E-mail address: yinlin@mail.ncku.edu.tw (Y.-Y. Lin).

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sudden malfunction of the attitude control during in-orbit operation. Although it is a stable algorithm, the B-dot method has the problems of excessive control period and ineffective power consumption as its control torque depends on the interactions between magnetic dipole moments generated by the spacecraft and Earth's magnetic field. Also, because of the uncontrollable magnitude and direction of the geomagnetic field, which is very weak, the magnetic torque induced is small and the desired control function is difficult to achieve.

Although many papers discussed the strategies on attitude stabilization and control, relatively little research has been reported in the study of detumbling schemes due to limited types of actuators one can apply other than magnetic torquers. The advent of new technologies in the torque wheel and the attitude sensor renders the possibility of developing a fast, power-saving method for the detumbling application. Nowadays, for efficient and accurate attitude control, most of the spacecrafts, large or small, carry a torque wheel [11–14]. It would be convenient and effective to detumble the spacecraft with the wheel and also help reduce the weight and size of the battery, the consumption of electric power, and the time of initial attitude acquisition because of the much larger torque available from the wheel. The approach is not without example as applying single rotor actuation with momentum transfer has been investigated in the flat spin recovery problem, another form of detumbling, for the dual-spin satellite [15–18].

In this paper, a two-part detumbling method using a torque wheel and a 3-axis magnetic torquer as actuating devices is presented. Part-1 of the method aligns a designated body axis with the total angular momentum, $\overrightarrow{H}_T$, bringing the tumbling spacecraft into single axis rotation as shown in Fig. 1, and then Part-2 despins the platform by transferring the momentum from it to the wheel or dumping most of the momentum, depending on the mission requirements or wheel characteristics. The body-fixed wheel with spinning axis along a designated body axis provides a control torque that induces the needed gyroscopic-like motion for the alignment in Part-1. In Part-2, the wheel also acts like a momentum sink, absorbing the platform angular momentum and despinning the spacecraft, and the magnetic torquer is mainly for dumping the momentum.

2. Attitude dynamics

To conveniently derive the proposed detumbling method, the attitude dynamics of a rigid spacecraft is formulated in terms of angular momentum [15–17]. Consider a rigid spacecraft as shown in Fig. 1. The center of mass of the spacecraft including the wheel is chosen as the origin of the set of body-fixed coordinates (i, j, k), which are also the principle axes of the spacecraft system. Total angular momentum of the spacecraft, $\overrightarrow{H}_T$, is defined as

$$\overrightarrow{H}_T = \overrightarrow{H}_P + \overrightarrow{h}_w, \tag{1}$$

where $\overrightarrow{H}_P = I_P \overrightarrow{\omega}$ is the angular momentum of the spacecraft platform and $\overrightarrow{h}_w = h_w j$ is the wheel angular momentum whose spin axis is parallel to the body j-axis. Also, $I_P = dia[I_1 I_2 I_3]$ is the principal moment of inertia matrix and $\overrightarrow{\omega} = \omega_1 i + \omega_2 j + \omega_3 k$ is the platform angular rate that can be measured from a three-axis gyro set onboard. The wheel angular momentum is $h_w = I_w(\omega_2 + \Omega)$, where I_w is the wheel axial moment of inertia about its spin axis and Ω is the wheel speed relative to the spacecraft platform. The transverse moment of inertia of the wheel along i- and k-axes is included in the I_P. Expressing in terms of momentum components, Eq. (1) becomes

$$\overrightarrow{H}_T = H_{1P} i + (H_{2P} + h_w) j + H_{3P} k, \tag{2}$$

and $H_T^2 = H_{1P}^2 + (H_{2P} + h_w)^2 + H_{3P}^2$, where $H_T = |\overrightarrow{H}_T|$.

Consider that the environmental disturbance torques in space are very small and can be ignored. As such, $\overrightarrow{H}_T$ is

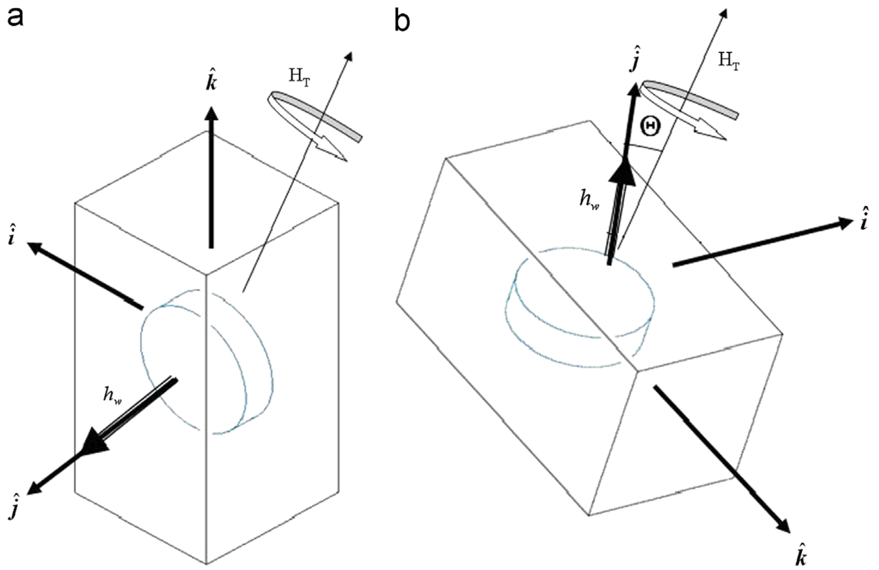

Fig. 1. Detumbling of the spacecraft from (a) initial state to (b) final state with $\Theta = 0$.