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CMG configuration and Steering Approach for Spacecraft Rapid maneuvers

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Abstract:

Earth observation satellites require rapid attitude maneuvering and stringent pointing accuracy for imaging payloads. This paper presents a configuration with Control Moment Gyros (CMG) and Steering scheme for rapid maneuvering of Indian spacecrafts. The maneuver considered is of track-to-track, where the spacecraft has an initial non-zero angular rate and perform the attitude maneuver to achieve the target imaging rate. Iterative algorithm is used for computing the maneuver time between various imaging targets. The CMG steering for avoiding the singularities during the time-optimal maneuvers has been addressed for meeting the stringent attitude control requirements. The Gain switching controller has been designed for high tacking performance during maneuver and imaging. The CMG steering approach, Maneuver control algorithms for on-board implementation is demonstrated by simulations.

Keywords: Reorientation Maneuvers, Agility, Control Moment Gyros, High Resolution Imaging.

1. INTRODUCTION

The Earth imaging satellites require rapid reorientation capability as well as precision pointing during image collection. An agile satellite is much more efficient by way of increased image throughput and stringent stability helps in quick turn-around of products to users without ground processing. Rapid retargeting maneuvers however are subjected to the physical limits of sensors, satellite structural rigidity, actuators and mission constraints. For a satellite to be agile it requires fast slew maneuvers in the range of 1-10 deg/sec. Unfortunately current ACS actuators such as reaction wheels are not able to provide this degree of agility efficiently, because their small control torque capability. Control Moment Gyros (CMG) on the other hand is more suitable for agile spacecrafts.

Control Moment Gyros (CMGs) are actuators that produce torque based on the principle of conservation of angular momentum. Since CMGs can produce large torque compared to Reaction wheels at same power consumption, CMGs are ideal actuators for agile spacecrafts. CMG contains a spinning rotor with constant angular momentum and its momentum direction can be changed by gimballing the spinning rotor. The resulting gyroscopic reaction torque is orthogonal to both spin and gimbal axes. The generated output torque is much greater than the input torque required to drive the gimbal motor. This property is well known as torque amplification of CMG (Margulies, G et al, 1978). CMGs are classified into Single Gimbal CMG (SGCMG), Double Gimbal CMG (DGCMG) and Variable Speed CMG (VSCMG). The SGCMG offer advantage in terms of torque, mechanism compared to DGCMG. VSCMG has extra degree of freedom and can be used for singularity avoidance. Spacecraft equipped with four Single Gimbal CMGs of pyramid arrangement has been used extensively because this configuration provides spherical momentum envelope and also having minimal redundancy (Wie.B et al. 2001) . For the typical imaging spacecrafts, the agility requirements are the order of 3-6 deg/sec. The Attitude Control System (ACS) needs to provide a stringent pointing accuracy during its planned imaging phase after completing the slew maneuvers. During slew maneuvers also, the specified tracking accuracy has to be met for image data downlink. The above mentioned stringent requirements are the driving factor for CMG configuration, steering and control algorithm design. Normally, the imaging spacecrafts require large control torques only along the roll and pitch (which are normal to payload view) to meet the cross track spot views and mosaic requirements compared to the payload axis.

The CMGs in pyramidal configuration (in which all gimbal orientation axes are different) presents the advantage in principle of having maximum momentum isotropy. However, the momentum envelope presents complex singular surfaces (Yoon, H et al, 2004). The pyramidal configuration presents many singular surfaces and difficult to navigate them. For providing the momentum capability along the two orthogonal spacecraft axes, the pyramidal configuration has to be flattened but with flattened pyramid it is not possible to independently adjust the capacities along the two axes of the pyramid base. The loss of one of the actuator leads to an agility envelope that is very asymmetrical and has a severe effect on agility.

The CMGs with parallel gimbal axes are the better choice in the view of asymmetric momentum requirement and better understanding of the singular structure of the parallel configuration (Kurokawa, H. 2007). The four CMGs are mounted in two pairs and each pair sharing common gimbal direction. By mounting the CMGs in this way, it is possible

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to independently adjust the momentum vectors. Hence the parallel CMG Configuration is suitable for rapid spacecraft maneuvers. The CMG steering law generates the gimbal rate command in response to the CMG torque command. One of the principal difficulties in using CMGs for spacecraft attitude control is the geometric singularity problem. Singularities arise when the torque vectors of CMGs are aligned on a plane, so that the CMG-Clusters cannot produce a control torque in the normal direction of the plane (Bedrossian N S et, al 1990).

The CMG singularities are classified as internal and external singularities. Internal singularities are the one which limits the spacecraft rate and usable momentum severely. Several methods are available to avoid or escape internal singular states. Singular Robust steering logic and null motion based laws are effective algorithm to avoid/escape singularities. The null motion is the one for those gimbal angles which produce zero torque. By utilizing the null motion of the CMG-cluster the internal singularities can be avoided (Bedrossian N S et, al 1990). In this paper, the CMG steering problem is solved using two planar systems. The component of momentum perpendicular to gimbal directions to be shared between the two pair of actuators is used to avoid the singularities or minimize the control degradation. The paper is organized as follows. Section 2 presents the spacecraft dynamics with CMGs. The Maneuver Reference algorithm is presented in Section 3. CMG configuration and Steering analysis are presented in section 4 and section 5. Simulation results in Sec.6 illustrate the performance of the proposed approach. Conclusions are presented in Sec.7

2. SPACECRAFT DYNAMICS WITH CMG

A simple mathematical model describing the attitude control of a rigid spacecraft equipped with a cluster of redundant CMGs is presented here. The following analysis is adapted from (Wie.B et al. 2001, Lappas, V, 2002). The CMG based spacecraft attitude control system block diagram is shown in Fig 1. Total angular momentum of the spacecraft is expressed as the sum of spacecraft main body angular momentum and the angular momentum of the CMG cluster is given by

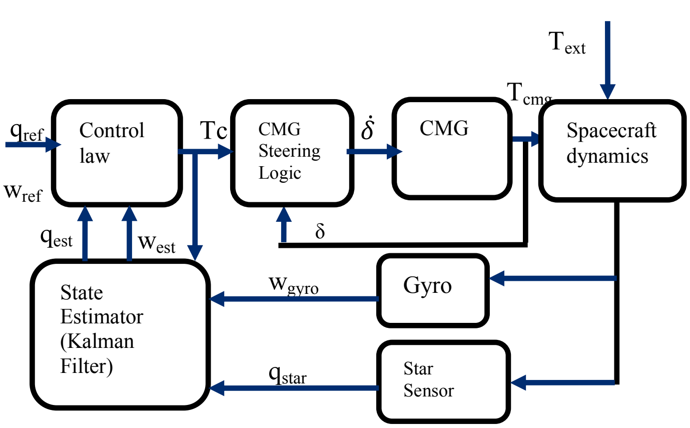

Fig 1 CMG based attitude control system

$$H = I\omega + h_{cmg} \tag{1}$$

where $H = (H_1\ H_2\ H_3)$ is the total angular momentum of the system with respect to the spacecraft's body-fixed control axis, I is the inertia matrix of the whole spacecraft including CMGs, $\omega = (\omega_1\ \omega_2\ \omega_3)$ is the spacecraft angular velocity vector and h_{cmg} is the total CMG angular momentum vector. The rotational equation of motion of a spacecraft can be described by

$$\dot{H} + \omega \times H = T_{ext} \tag{2}$$

$$\omega \times H = \begin{bmatrix} 0 & -\omega_3 & \omega_2 \\ \omega_3 & 0 & -\omega_1 \\ -\omega_2 & \omega_1 & 0 \end{bmatrix} \begin{bmatrix} H_1 \\ H_2 \\ H_3 \end{bmatrix} \tag{3}$$

Where T_{ext} is the sum of external disturbance torques acting on the spacecraft including the gravity gradient, solar pressure and aerodynamic torques defined in the same body-fixed control axes. Substituting Equation (1) into the Equation (2), we get

$$(I\dot{\omega} + \dot{h}_{cmg}) + \omega \times (I\,\omega + h_{cmg}) = T_{ext} \tag{4}$$

Rearranging this equation by introducing the internal control torque generated by CMG cluster $u = (u_1, u_2, u_3)$, we have

$$(I\,\dot{\omega}) + \omega \times (I\,\omega) = T_{ext} + u \tag{5}$$

$$\dot{h}_{cmg} + \omega \times h_{cmg} = -u \tag{6}$$

The control torque "u" is generated using Proportional Derivative controller (PD). The gain switching controller has been designed to minimize the tracking error during maneuver. Maneuver trajectory is defined by the spacecraft agility which is dictated by the rate and acceleration capabilities. Once the trajectory is defined, close tracking is required to minimize the attitude and rate errors at the target image point. For the maneuver high bandwidth controller is used. After completion of maneuver, transients settle fast due to minimum tracking error and more weightage is given for control loop stability with noise reduction. For this region low gains are used for controller and state estimator.

The spacecraft kinematics equations relating the rates of change of quaternion to the angular velocity ω of the spacecraft is given by

$$\dot{q} = \left(\tfrac{1}{2}\right)[\omega(\mathrm{t})] \otimes \mathrm{q(t)} \tag{7}$$

where

$$[\omega(\mathrm{t})]\otimes = \begin{bmatrix} 0 & \omega_3 & -\omega_2 & \omega_1 \\ -\omega_3 & 0 & w_1 & \omega_2 \\ \omega_2 & -\omega_1 & 0 & \omega_3 \\ -\omega_1 & -\omega_2 & -\omega_3 & 0 \end{bmatrix} \tag{8}$$

Then, the desired CMG momentum rate is selected as

$$\dot{h}_{cmg} = -\omega \times h_{cmg} - u \tag{9}$$