MIXED CONTROL MOMENTUM GYROSCOPES AND REACTIONS WHEEL BASED ATTITUDE CONTROL SYSTEM

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This paper describes a mixed Control Moment Gyroscope and Reactions Wheels based AOCS developed for COSMO-SkyMed Second Generation. The proposed architecture and control structure permits to optimal coordinate the functioning of the two actuators in order to maximize the exploitation of the CMG performances. The paper results show that the proposed solution permits to dramatically increase the platform’s agility capability.

The recent evolution of advanced Earth observation missions has been directed toward technological means able to extend the access area for image acquisitions, to support the capability of “mosaic” acquisitions (i.e. radar and optical systems) of the interest area, to reduce the “revisit time” of a target on ground, to reduce the manoeuvring time to get consecutive targets situated rightmost and leftmost w.r.t. the spacecraft fly path.

Whatever might be the specific mission characteristic, the basic feature which allows an efficient pointing functionality is the spacecraft “agility”. Agility represents the motion of the platform on its three axes with the fastest speed rate. It is realized by attitude control actuators which are dimensioned according to the spacecraft’s mass and inertia. The agility, meaning the flexibility and the ability to quickly move the satellite, becomes constantly a constraint of the project. To this extent, the future generation of both optical and radar LEO (Low Earth Orbit) satellites will require attaining of rotation speed between 0.5°/s and 5°/s (depending on the satellite mass properties).

Typically agility has been extensively exploited in the field of optical spacecraft, where a relatively low payload mass is not particularly demanding in terms of actuation force: moderate agility has been reached by means of Reaction Wheels in mission as QuickBird, IKONOS, GeoEye (panchromatic and multispectral payload). Conversely very high agility has been obtained on DigitalGlobe WorldView 1 and 2 spacecraft, with a relative agility up to 17 times greater w.r.t. the previous optical satellites thanks to the best mechanical actuation technology present nowadays: the Control Momentum Gyro (CMG).

Currently, a CMG meeting the above operational capability is under qualification campaign in the frame of COSMO-SkyMed Second Generation (CSG) satellites development. CSG is the most important Italian programme for Earth Observation from space. The program is funded by the Italian Space Agency (ASI) and the Italian Ministry of Defence (MoD).

CMGs momentum exchange actuators are able to considerably reduce the spacecraft manoeuvres duration both in elevation and in azimuth. The adoption of CMGs for 3-axes attitude control requires the implementation of complex control algorithms on the on-board computer in order to compute the actuator commands. In typical Earth Observation’s missions, as for radar satellites,

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it’s not always requested to achieve agility along the three axes. In these cases the best solution, in terms of costs, algorithm complexity and reliability, is the usage of an actuator system based on mixed configuration Reaction Wheels (RWs) and CMGs, where the CMG are in charge of providing agility along one preferred direction.

In this paper it will be presented an Attitude Control System based on the coordinated usage of CMGs together with a cluster of four RWs. In the proposed configuration the CMGs are placed so that the output torque lies on a plane containing the desired spacecraft steering directions. Moreover the CMGs are actuated in order to produce an angular momentum variation mainly in one fixed direction, called ‘scissor axes’.

Whilst the CMGs are used to enhance the platform agility, the Reaction Wheel assembly neutralizes the errors induced by CMG actuation (e.g. CMG axis misalignments and non-diagonal terms of the spacecraft inertia matrix) and external disturbances. The configuration detailed in this paper allows the usage of simplified and reliable actuators management, in particular the CMGs commands are based on strengthened and deterministic steering laws; in addition it allows minimizing the number of CMGs limiting their usage to preferred plane. A Detailed description of the algorithms and the actuators has been omitted to protect confidential industrial information.

INTRODUCTION

The proposed control strategy foresees the coordinated use of Reaction Wheels and Control Momentum Gyroscopes to achieve the platform stabilization and agility. The Reaction Wheels Assembly (hereafter called RWA) is composed of four units arranged in a pyramidal configuration used to guarantee the three axis stabilization, compensation of the cyclic torques, external disturbances and high-accuracy pointing control.

![RWA Normalized angular momentum envelope](image)

**Figure 1. RWA normalized angular momentum envelope.**

The Control Momentum Gyroscope Assembly (hereafter called CMGA) is composed by two units, disposed in a “scissored pair” configuration (see picture below), having the scope to provide the angular momentum and torque to sustain the platform agility requirements on roll and pitch axes.
The CMGA configuration allows continuously providing torque only on the x-y plane and it presents an internal singular point equivalent to the zero angular momentum condition. In this configuration the two CMGs are actuated in order to produce a variation of angular momentum mainly in one constant direction, called ‘scissor axis’; this is performed by actuating the two CMGs with equal but opposite gimbal rate commands. When an agile maneuver is requested the AOCS splits the controller torque command between the RWA and CMGA in such a way that the CMG assembly is in charge to provide the large torque and momentum contribution. The main task of the RWA is to compensate the feedback controller errors due to non modelled phenomena and other minor effects. To fast repoint the antenna line-of-sight across the satellite ground track or to perform stereo images to continuously acquire a point of interest, the platform shall perform almost pure maneuvers along the principal axis of inertia.
balancing masses are added during the spacecraft integration phases, nevertheless the off-diagonal elements can be the in the order of 10%-15% w.r.t. the main-diagonal elements. In case of a single axis slew, in which the spacecraft rotates along the Roll axis, performed using a Bang-Bang torque profile, as depicted in following figures, the maximum control torque is kept constant along the desired direction.

![Image](image.png)

**Figure 4. Bang-Bang reference trajectory.**

To evaluate the magnitude of the spurious torque we replace the reference attitude trajectory into the spacecraft dynamics equations.

\[
\omega_{ref} \ t = 0 \quad , \quad \omega_{ref} \ t = 0
\]

The dynamic equation for a rigid body (the contribution of the flexible appendages is neglected) can be easily described as follows:

\[
T_c \ t = J \omega \ t + \omega(t) \times J \omega \ t + H_{SC}(t)
\]

(1)

where HSC is the total angular momentum stored by the momentum exchange actuators. Combining the previous equations, we obtain that the torque disturbance on the y and z axis depends on the torque command on the x axis and it is weighted with the inertia tensor elements as follows:

\[
T_y = f_{yx} \omega_x + f_{yx} \omega_x^2 = \frac{f_{yx}}{f_{xx}} T_{CMG} + f_{yx} \omega_x^2
\]

\[
T_z = f_{zx} \omega_x + f_{yx} \omega_x^2 = \frac{f_{zx}}{f_{xx}} T_{CMG} + f_{yx} \omega_x^2
\]

(2)

For the sake of simplicity the angular momentum stored on board is assumed to be zero. This assumption is true if the RWA is actuated in order to compensate the orbital angular momentum.
The cross-coupling effect due to the off-diagonal elements disappears if we choose a coordinate system where the principal axis of the rotating rigid body and the components of the angular momentum are aligned. In this new reference system we can perform pure rotation around the principal axes.

The S/C angular momentum expressed in the platform reference frame is

$$ H^G = \begin{bmatrix} J_{xx}^G & -J_{xy}^G & -J_{xz}^G & \omega_x^G \\ J_{yx}^G & J_{yy}^G & J_{yz}^G & \omega_y^G \\ -J_{zx}^G & -J_{zy}^G & J_{zz}^G & \omega_z^G \end{bmatrix} $$

where the inertia tensor is computed around the center of mass. The previous equation implies that the angular momentum and the angular rate are not parallel. Since it is always possible to find a reference frame in which the inertia tensor is diagonal we can write

$$ H^G = J^G \omega^G = A_0^G H^0 = A_0^G J^0 \omega^0 = A_0^G j^0 A_0^G \omega^G $$

(4)

Where J0 is the diagonal inertia matrix. Factoring by grouping we obtain that the inertia matrix expressed with respect to the center of mass is as follows

$$ J^G = A_0^G j^0 A_0^G $$

(5)

Hence, if we want to obtain a pure rotation around a preferential axis without introducing any torque disturbance we have to find the rotational matrix $A_0^G$. In case of a Roll maneuver the unit vectors composing the rotational matrix can be obtained as follows:

$$ v_x = \frac{j^G u_x}{j^G u_x} \quad v_z = v_x \times u_y \quad v_y = v_z \times v_x $$

(6)

From the previous considerations it is clear that, in order to minimize the unwanted torque disturbances, it is advantageous to choose the preferred CMGA actuation axis coincided with a unit vector of the Rotational Matrix $A_0^G$.

Since in CSG the CMGs are disposed on the x-y plane and the inertia tensor component $J_{zx}$ is not null, we can only align the CMGA preferred actuation direction along the projection of $\hat{v}_x$ on the S/C x-y plane.

OPTIMIZED SCISSORED PAIR CONFIGURATION

Once the scissor axis s has been fixed, the home position for both CMGs can be defined: in such position the angular momentum of the two CMG lies on the axis t (normal to scissor axis) with opposite directions. The gimbal angles $\gamma^0_t$ corresponding to this position are named gimbal home values and they are fixed once the scissor axis is defined.
Figure 5. CMGA general configuration.

- $s$ is the scissor axis direction;
- $t$ is the direction normal to the scissor axis;
- $g_i$ is the gimbal axis direction of the $i$-th CMG;
- $\gamma_i$ is the gimbal angle of the $i$-th CMG with respect to the zero position of the unit;
- $\gamma_i^0$ is the gimbal home of the $i$-th CMG;
- $\theta_s$ is the scissor angle;
- $\delta_i$ is the gimbal angle of the $i$-th CMG with respect to the home position;
- $h_i$ is the angular momentum of the $i$-th CMG.

The following relationships can be derived:

\[
\begin{align*}
\gamma_i &= \gamma_i^0 + \delta_i \\
\gamma_i &= \delta_i \\
\gamma_i^0 &= \theta_s \\
\gamma_2^0 &= \theta_s + \pi \\
\theta_s &= -\frac{\text{atan} \frac{s_y}{s_x}}
\end{align*}
\]  

(7)

Note that the previous equations on the gimbal home positions are valid only in case the two CMGs have the same flywheel speed direction. Another control approach consists in polarizing the CMGs flywheels with opposite speed directions; in this case the relationship between gimbal angle and home position is the following.

\[
\gamma_1^0 = \gamma_2^0 = \theta_s
\]  

(8)

It has to be underlined that the CMGA rest position is always a zero momentum configuration.
TORQUE AND ANGULAR MOMENTUM MANAGEMENT

In order to generalize the gimbal command algorithms, it is useful to write the equations of the angular momentum and angular momentum variation of the CMG assembly in the reference defined by \( s \) and \( t \).

Starting from the CMG orientation reported in the previous paragraph, it can be derived the angular momentum with respect to the scissor axes \( \hat{s} \) and \( \hat{t} \):

\[
H_t(t) = h_1 \cos \delta_1(t) - h_2 \cos \delta_2(t) \\
H_s(t) = h_1 \sin \delta_1(t) - h_2 \sin \delta_2(t)
\]  

(9)

Performing the time derivative of the previous equations and considering that \( h_1 = h_2 = H \) we obtain:

\[
H_t(t) = -h_1 \delta_1(t) \sin \delta_1(t) + h_2 \delta_2(t) \sin \delta_2(t) \\
H_s(t) = h_1 \delta_1(t) \cos \delta_1(t) - h_2 \delta_2(t) \cos \delta_2(t) \\
H_t(t) = -H \delta_1(t) \sin \delta_1(t) - \delta_2(t) \sin \delta_2(t) \\
H_s(t) = H \delta_1(t) \cos \delta_1(t) - \delta_2(t) \cos \delta_2(t)
\]  

(10)

Considering that, in scissored management the command is \( \delta_2 = -\delta_1 \) and \( \delta_2 = -\delta_1 \).

\[
H_t(t) = 0 \\
H_s(t) = 2H \delta_1(t) \cos \delta_1(t)
\]  

(11)

As we can see the imposed gimbal rate law, that simplify the CMGs steering law, allows actuating torque only along the scissor axis direction. For a given torque request \( T \), the gimbal rate command can be derived as follows:

\[
T \frac{t}{T_s(t)} = 0 \\
\frac{\delta_1(t)}{\delta_2(t)} = \frac{T_s(t)}{2H \cos(\delta_1(t))}
\]  

(12)

From the integration of the previous equations it can be inferred the gimbal angles variation profile:

\[
\delta_1(t) = \frac{H_s(t)}{2H} \ln \left( \tan(\frac{\delta_1(t)}{2}) + \frac{\pi}{4} \right) \\
\delta_2(t) = -\delta_1(t)
\]  

(13)

where \( H_s(t) = \int_t^{t+\Delta t} T_s dt \).

In case it is requested to change the scissor axis (i.e. sequential roll and pitch manoeuvres), the CMG assembly can be easily reconfigured by using the so-called null-motion command, which allows to move the CMGs in any of the \( \infty \) zero-momentum configurations. Therefore the gimbal command becomes:

\[
\delta_2(t) = \delta_1(t)
\]  

(14)

EXAMPLE: ROLL MANOEUVER

As previously described during the normal pointing mode the CMGs are actively used in the AOCS control loop to perform roll and pitch manoeuvres. When a maneuver request is received by the on-board computer the CMGA is reconfigured, if necessary, in order to align the scissor axis along the desired maneuver direction. Once the assembly is correctly aligned the AOCS controller calculates the torque request \( T_s(t) \) along the scissor axis as follows:
\[ T_{\text{cmg}}(t) = -T_c(t) \cdot s \]
\[ T_{\text{rwa}}(t) = T_c(t) - T_{\text{cmg}}(t) + T_{\text{CL}}(t) \]

where \( T_c(t) \) derives from (1) and \( T_{\text{CL}}(t) \) is the feedback controller contribution.

In the following figure (fig. 6) is shown the simulated roll reference trajectory; the first manoeuver is performed using only the RWA, while the others using both RWA and CMGA.

![Figure 6. Reference trajectory.](image)

In figure 7 are depicted the torque provided by the RWA and CMGA to the platform when the scissor axis is perfectly aligned with the manoeuver axis. As we can see the CMGA produces most of the requested torque on the Roll axis, while the RWA, in accordance with equation (2), compensates the effect of the off-diagonal elements of the inertia matrix. This means that the platform agility performances are strongly limited by the RWA capability, since an increment in the torque request along the manoeuver axis will cause the actuators saturation.

The same simulation has been performed arranging the CMGA scissor axis along the optimal direction. As we can see in figure 8 the torque provided by the RWA on the Pitch axis is one-third with respect to the previous case. The contribution on the Yaw axis is unvaried, since the CMGA operates only on the x-y plane.
CONCLUSIONS

The adoption of the Control Momentum Gyros (CMG) in the frame of COSMO-SkyMed Second Generation (CSG) avionics project constitutes a new development and a strategic feature for the improvement of spacecraft platform’s capabilities for new products.

The space qualification of these CMG actuators, designed and developed entirely by TAS-I at Rome premises, represents a new technological enhancement, which will guarantee an important asset for the platform’s attitude maneuverability.

The improvement of the spacecraft platform agility through the CMGs implementation in the PRIMA (Piattaforma Riconfigurabile Italiana Multi Applicativa) platform, developed under an ASI Contract, will represent a strategic asset for the national industry both for radar or optical missions.

In terms of performance, CMG/RWA actuators are able to enhance platform’s torque in order to improve the spacecraft pointing flexibility and agility; in this way it is possible to cope with the CSG requirements regarding image acquisition capabilities.

The capability based on CMG-RW synergic coupling, described in this paper, radically increases the agility characteristic of the PRIMA platform, allowing the exploitation of new mission scenarios. The proposed control strategy, through the selection of an optimal scissor axis, allows to take advantage of the peculiarity of both actuators and, in particular, increases the ability of the system to exploit the CMGA capabilities, while using the RWA to achieve a fine and stable pointing. The proposed solution allows obtaining a spacecraft fast repointing and continuous acquisition maneuver along any direction on roll-pitch plane.

Further developments will foresee the implementation of full CMG based AOCS able to cope with both the 3-axis stabilization and agility requirements.
REFERENCES


