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Simulation of Three Axis Attitude Control Using a Control Momentum Gyroscope for Small Satellites

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Abstract- **Control moment gyroscope is a spacecraft attitude control actuators which act as torque amplifier. It is suitable for three axis slew maneuvering by providing the necessary torques via gambling a spinning flywheel. Control moment gyroscope is considered to be more efficient than current actuators such as reaction/momentum wheels in term of power consumption and slew rate. A major disadvantage encountered with the use of the control moment gyroscope is the possibility of singularities for certain combinations of gimbal angles. This paper presents the simulation results on the performance of a control moment gyroscope cluster for 3-axis attitude control for agile satellites.**

Index Terms- **Simulation, Attitude, Control, Momentum, Gyroscope, Satellite.**

I. INTRODUCTION

Attitude control system is the process of orienting the spacecraft in a specified, predetermined direction (pointing) during mission despite the external disturbances. It consists of two areas; attitude stabilisation which is the process of maintaining an existing orientation and attitude maneuver control, which is the process of controlling the orientation of the spacecraft from one attitude to another.

Current small satellites accomplish the mission with the main actuators (magnetorquers, reaction-momentum wheels and thrusters) with a slew rate of 0.1deg/sec – 1deg/sec and an accuracy of 0.1deg – 5deg. The objective for future missions is to increase the agility (high degree of spacecraft maneuverability) and the slew rate by an order of magnitude 1 deg/sec – 10 deg/sec dedicated by future missions:

- Stereo-imaging, tactical imaging (military imaging);
- Interplanetary probes, formation flying;
- Commercial imaging.

The required agility and slew rate can not be supplied but current technologies, we need to develop an alternative, more capable actuator based on Control Momentum Gyros.

Most space missions require satellites to accomplish their missions while and being the smallest size possible. This includes Earth observation with high resolution for certain missions imaging, satellite inspection and interplanetary exploration satellites miniaturized.

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The 3 axis attitude control has been tremendous progress in the last two decades. However there is a need to develop other attitude control system news missions.

The majority of these missions require great agility. This increases agility considerably the operational envelope and efficiency of the satellite and can remarkably increase the return of mission data. The attitude control system is an essential for all types of satellites. Design such a system for missions requiring high performance with agility while taking into consideration the physical constraints and the small size of satellite is a very difficult task. Since agility involves very fast maneuvers of the order of 1 - 10 deg/sec, it becomes evident that the types of current actuators (reaction /momentum wheels) does not allow such maneuvers, however, the CMGs (control moment gyros) that are capable of providing such maneuvers were never used for microsatellites until the launch of the Turkish microsatellite Bilsat on the 27 September 2003, which was the first experiment of CMGs on a microsatellite.

Until now, the CMGs have been only deployed on large satellites (MIR, USSR, 1966; KH-11, USA, 1966; SKYLAB, USA, 1973). These CMGs were of great size, mechanically complicated and very expensive

Because of the inherent problems of singularities CMGs, and to a lesser torque amplification for satellites performing rapid maneuvers, use of this type of actuator has long been considered inappropriate for small satellites.

Recently, this situation began to change with the development of the mini CMGs taking advantage of the benefits, particularly in terms of storage capacity of the angular momentum and the electric energy consumption. Thus the mini-CMGs become more attractive for agile Earth observation microsatellites. In addition to advantages in terms of size and electric power consumption, torque amplification makes appropriate CMGs for microsatellites (<100 kg) demanding in terms of agility.

The attitude control system using CMG is similar to the wheels on the principle of exchange of angular momentum between controlled internal systems and the satellite subjected to disturbances.

There are several types of CMGs. When the wheel speed is variable, it is called then VSCMG (Variable Speed CMG), which takes the advantages of a CMG and a reaction wheel, although the speed variation provides one additional freedom degree, they are also more complicated to design and less reliable. Depending on the number of axes disk CMGs, there are two types of

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SGCMG (Single Gimbal CMG) and DGCMG (Double Gimbal CMG). The type and also the number and arrangement of CMGs used by the attitude control system are a compromise between performance, cost, reliability, performance and complexity of the control algorithm.

The SGCMGs and the VSCMGs are most efficient in terms of generation torque but SGCMGs require at least four units to ensure control on the three axes avoiding singularities. By cons, with VSCMGs, although three are sufficient, they are very complex. DGCMG with the advantage of amplification torque is lost. They are heavier, and the mechanical engineering is more complicated. In Moreover, they consume more energy.

A singular state for a CMG is a gimbal angle combination at which no torque is possible along a certain direction. During maneuvering, the gimbal angles should be steered away from the singular states in order to be able to generate any commanded torque. Many researchers have studied and proposed a variety of methods to avoid or escape the CMG singularities [1-12].

The SCMGs require a minimum of four units for full 3-axis control in order to avoid singularities [13]. SGCMGs have been thoroughly studied in the past and have been base lined to be used in future space missions [14-15].

The CMGs could change the purpose for which small satellites are developed. Agility increases (high slew rates) the operational envelope of satellite and enables to collect more scientific data using less resources. This means in practice increasing scientific and commercial value of the satellite.

One of the most severe constraints for small satellites is limited time for data transmission. The CMGs will enable small satellites to perform pointing to earth over time.

The CMGs are ideal candidates for these missions and this paper investigates the use of such sophisticated actuators for small satellites.

Figure 1 presents the single gimbal control momentum gyroscope.

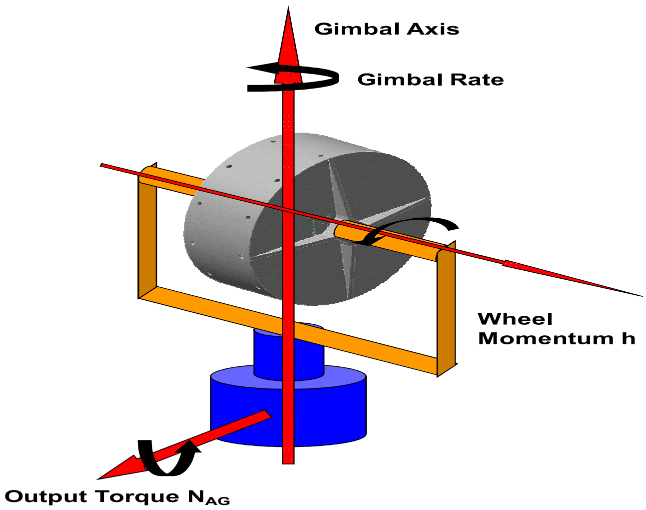

Fig. 1. Single Gimbal CMG

Figure 2 presents the double gimbal control momentum gyroscope.

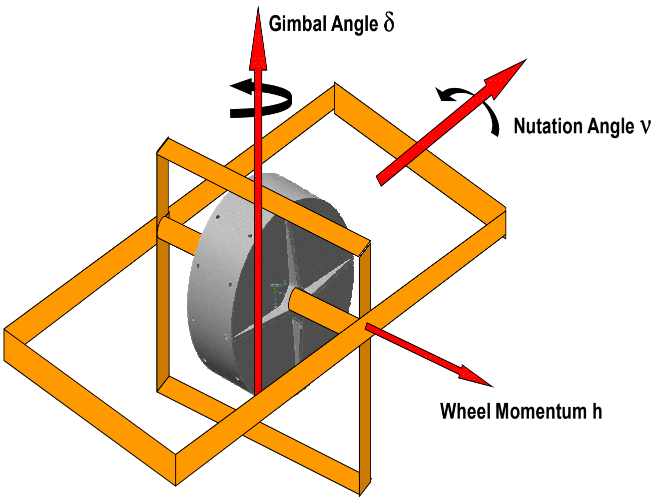

Fig. 2. Double Gimbal CMG

II. Mathematical Description of the Attitude Control using CMGs System

The attitude control using CMGs is performed usually in two steps: In the first step, the necessary torque required for CMG training devices to perform the attitude maneuver must be determined, and secondly, the torque must be produced by the CMG, then the control strategy contains two control loops:

Outer loop**:** which should generate the virtual torque.

Inner loop**:** which is able to produce the torque required (actual control torque) while avoiding the singular configurations, and taking account other physical constraints of attitude control system.

The controllability of the spacecraft must be maintained at all times and modeling the outer control loop must limit the CMG torque to avoid going near CMG singular situations.

The outer loop should not also force the system to produce a CMG torque given if this may lead to an inevitable singularity.

The role of the internal control loop is to generate the necessary precession speed so that the system produces the CMG control torque required by the loop of the external control.

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Figure 3 presents the attitude control system using CMGs.

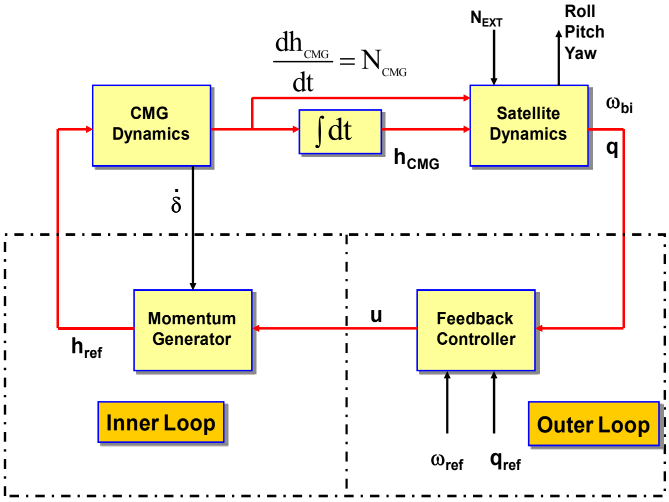

Fig. 3. Attitude Control System using CMGs

III. Three Axis Attitude Control Using CMG

One single gimbal control moment gyro (SGCMG) is insufficient to ensure 3-axis control as the angular momentum h is still on the plane rotation described by the angle δ. Thus, to provide 3- axis attitude control must be at least 3 CMGs. However, the rotors of CMGs are designed so that their order is not possible in certain directions, which correspond to problems singularities. To overcome to this problem is uses a 4th CMG to provide redundancy. It is arranged in a pyramidal configuration, as shown in the figure below:

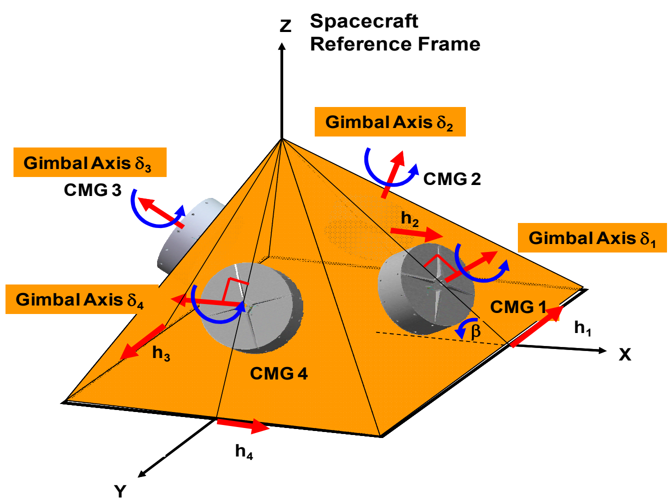

Fig. 4. Pyramidal configuration of 4 SGCMG for 3-axis attitude control

With this configuration, a fourth degree of freedom in the attitude control is introduced by the 4th CMG.
Each pyramid face is inclined at an angle β = 54.73 deg from the horizontal, which can give an angular momentum equal to h on 3 axes and a angular momentum envelope almost spherical.

The CMG angular momentum is

$$h = h_0 \begin{pmatrix} -\cos\beta\sin\delta_1 \\ \cos\delta_1 \\ \sin\beta\sin\delta_1 \end{pmatrix} + h_0 \begin{pmatrix} -\cos\delta_2 \\ -\cos\beta\sin\delta_2 \\ \sin\beta\sin\delta_2 \end{pmatrix} + h_0 \begin{pmatrix} \cos\beta\sin\delta_3 \\ -\cos\delta_3 \\ \sin\beta\sin\delta_3 \end{pmatrix} + h_0 \begin{pmatrix} \cos\delta_4 \\ \cos\beta\sin\delta_4 \\ \sin\beta\sin\delta_4 \end{pmatrix} \tag{1}$$

where δ is the precession angle.

The torque generated by the CMGs is

$$N_{CMG} = \dot{h} = J(\delta)\dot{\delta} \tag{2}$$

where $J(\delta)$ is a 3 x 4 Jacobian matrix

$$J(\delta) = \frac{\partial h}{\partial \delta} = \begin{bmatrix} -\cos\beta\cos\delta_1 & \sin\delta_2 & \cos\beta\cos\delta_3 & -\sin\delta_4 \\ -\sin\delta_1 & -\cos\beta\cos\delta_2 & \sin\delta_3 & \cos\beta\cos\delta_4 \\ \sin\beta\cos\delta_1 & \sin\beta\cos\delta_2 & \sin\beta\cos\delta_3 & \sin\beta\cos\delta_4 \end{bmatrix} \tag{3}$$

$\dot{\delta}$ is computed using the inverse kinematic solution (Pseudoinverse)

$$\dot{\delta} = J(\delta)^T \left[J(\delta)J(\delta)^T \right]^{-1} \dot{h} \tag{4}$$

Then,

- Generate commanded torques and also avoid 'singular' sets of gimbal angles, where no torque is produced.
- 'Steer' angles to more favorable directions, escape, avoid or transit through singularities.

IV. Simulation Results

The simulation results presented in this paper were obtained with a simulator that implements the dynamics and kinematics of the satellite using C code, MATLAB and SIMULINK. The satellite in a low Earth orbit was used as an example during these simulations.

The satellite dynamics are modeled using Euler's equations for a rigid body motion under the influence of internal and external torques. The torques considered are those generated from a 4-SGCMG in pyramid configuration.

The following MOI matrix is assumed during the test

$$\begin{bmatrix} 33.35 & \pm 0.1 & \pm 0.1 \\ \pm 0.1 & 34.04 & \pm 0.1 \\ \pm 0.1 & \pm 0.1 & 32.09 \end{bmatrix} kgm^2$$

The main requirements for the simulations are as follows:

- Selection of h and max. gimbal rate is a trade-off between performance, size and singularity avoidance,
- Keep h as small as possible (less mass, volume),
- Avoid using large gimbal rates leading to large gimbal angle excursions, thus singularities,

- A max. gimbal rate of 7.5 deg/sec is used which is larger than the max. angular rate of satellite when doing a 3-axis slew maneuvers,
- Ensures torque amplification throughout a maneuver.

Figures 5 to 11 display the results from typical 3-axis control momentum gyro slew and pointing maneuvers during an orbit. The CMG torque is saturated at ± 15 mNm and the CMG momentum at ± 0.42 Nms. A rate quaternion feedback controller is used to track certain attitude commands. The simulations starts with 10 deg roll, -8 deg pitch and 5 deg yaw angles, the initial CMG momentum is $h_0 =$ 0.35 Nms and the initial gimbal angles is [-90 180 90 0] deg. A simultaneous -30 deg roll, 20 deg pitch and 45 deg yaw slew maneuver is then commanded and next individually commanded back in a reversed order. A singularity avoidance law based on inverse singularity robustness SR [2] is used. The reference attitude angle is reached after about 100 seconds. Maximum gimbal angle excursions reached ± 90 deg and maximum torque of ~ 15 mNm is required. The attitude response look well behaved without large overshoot and the pointing errors are very small.

A more realistic simulation with an attitude estimator and external disturbances torques must actually be done to investigate the size of any pointing errors.

The feedback control law [16] for SGCMG is

$$N_{SGCMG} = \begin{bmatrix} 10.0\omega_{ox} + 1.0q_{1e} \\ 10.0\omega_{oy} + 1.0q_{2e} \\ 10.0\omega_{oz} + 1.0q_{3e} \end{bmatrix} \qquad (5)$$

where,

N_{SGCMG} : Commanded SGCMG torque vector

q_{ie} : Vector part of the error quaternion, where the error quaternion is obtained through quaternion multiplication of the attitude quaternion and the commanded (reference) quaternion.

Figure 12 presents the control momentum gyroscope simulator.

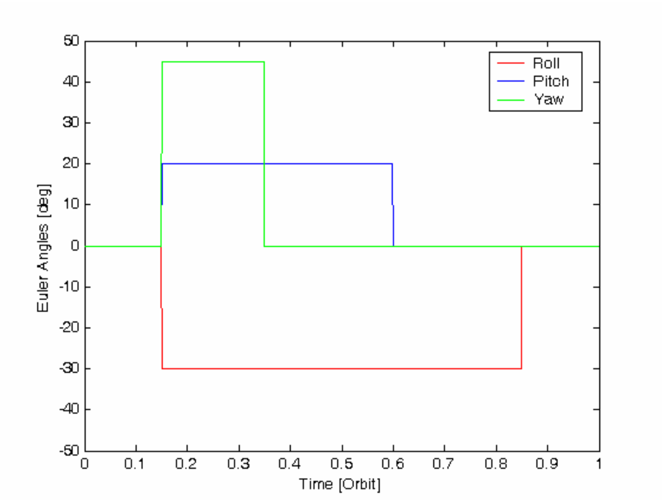

Fig. 5. Command attitude during 3-axis slew maneuvers

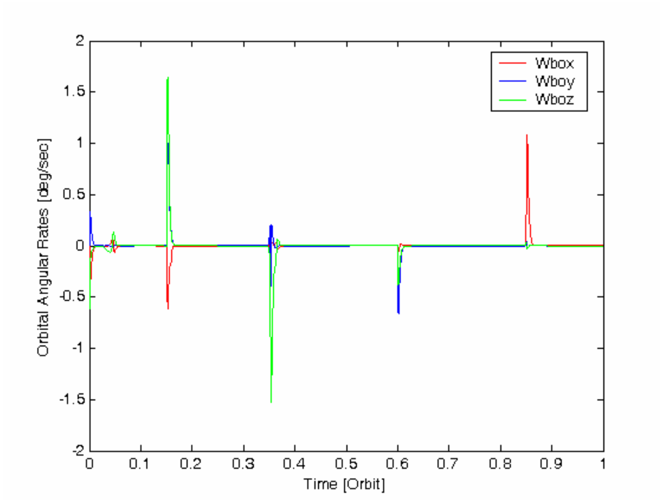

Fig. 7. Orbital angular rates using 3-axis SGCMG control

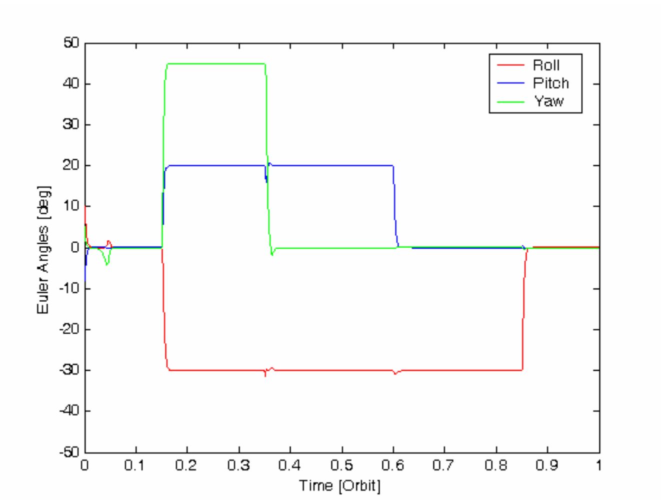

Fig. 6. Attitude manœuvres using 3-axis SGCMG control

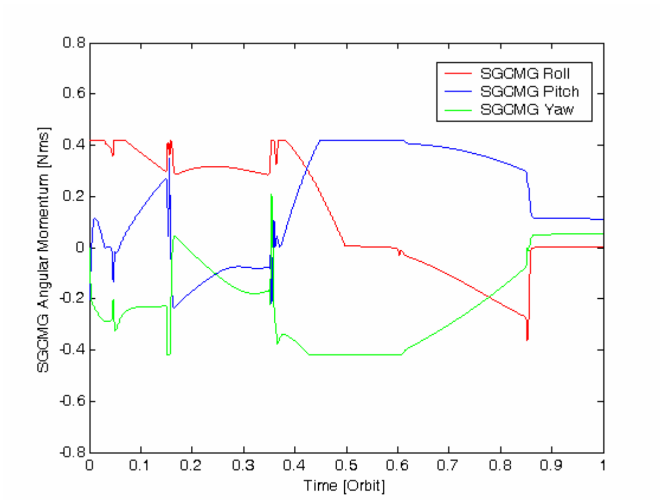

Fig. 8. SGCMG angular momentum during 3-axis slew maneuvers

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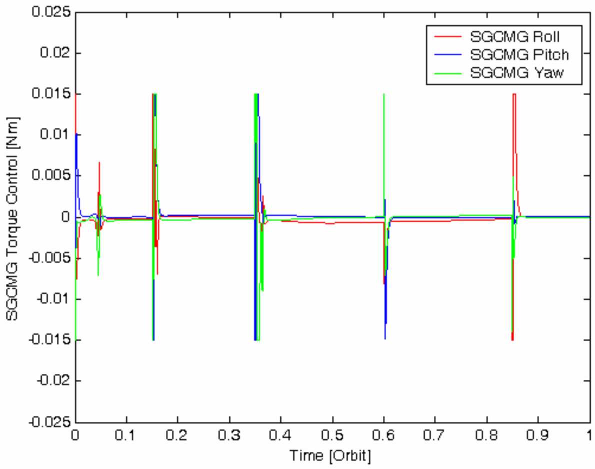

Fig. 9. SGCMG torque during 3-axis slew maneuvers

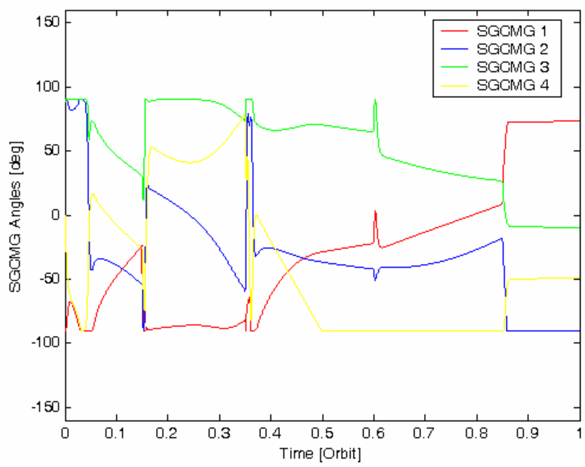

Fig. 10. SGCMG angles during 3-axis slew maneuvers

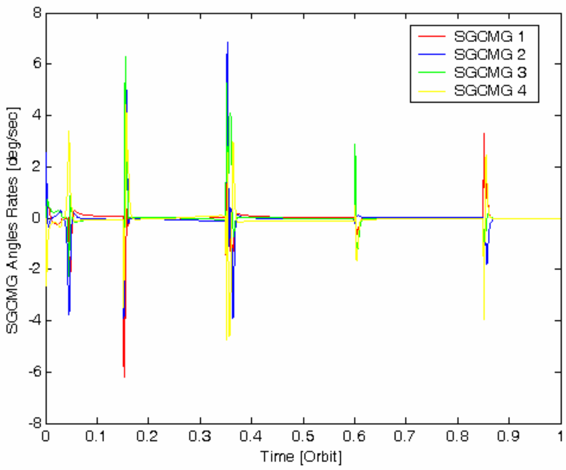

Fig. 11. SGCMG angles rates during 3-axis slew maneuvers

V. Conclusion

The study confirms the ability of the control moment gyroscope system to provide agility in term of high degree of spacecraft maneuverability and high spacecraft slew rates. A system of 4 control moment gyroscopes in pyramid arrangement is used to demonstrate full 3-axis control.

To conclude, the control moment gyroscope system can be attractive, efficient, novel, alternative attitude control systems for agile small satellites mission but it can be extended for general microsatellite missions.

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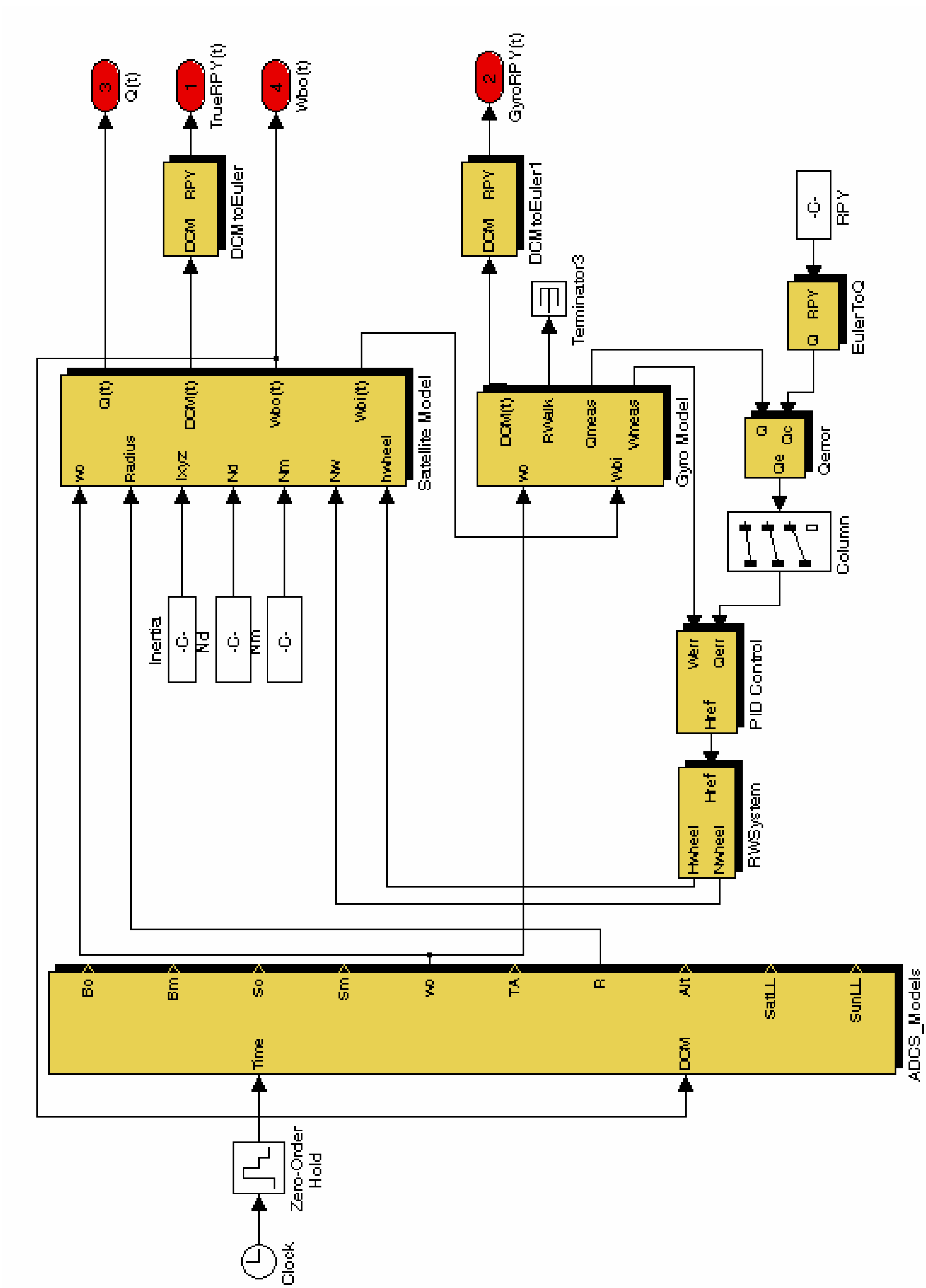

Fig. 12. Control momentum gyro simulator