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Spherical gyroscopic moment stabilizer for attitude control of microsatellites

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ABSTRACT

This paper presents a new and improved concept of recently proposed two-degrees of freedom spherical stabilizer for triaxial orientation of microsatellites. The analytical analysis of the advantages of the proposed mechanism over the existing inertial attitude control devices are introduced. The extended equations of motion of the stabilizing satellite including the spherical gyroscope, for control law design and numerical simulations, are studied in detail. A new control algorithm based on continuous high-order sliding mode algorithms, for managing the torque produced by the stabilizer and therefore the attitude control of the satellite in the presence of perturbations/uncertainties, is presented. Some numerical simulations are carried out to prove the performance of the proposed mechanism and control laws.

1. Introduction

The control systems of angular movement of satellites or, in other worlds, the attitude control of satellites respect to their mass center, usually are described as the most complicated and responsible part of the on-board apparatus. The efficiency of a satellite and, as a result, the efficiency of its practical tasks essentially depends on the functional possibilities of the attitude control systems and their technological and performance characteristics.

Basically, to carry out the active attitude control task of a satellite two types of actuators are used: reactive devices, which create external reactive forces like propulsion engines; and inertial devices, which create internal reactive moments like reaction wheels and control moment gyros. When the requirement for constant orientation of a satellite is set, the use of inertial devices is forced. This is explained by the fact, that the summary mass of control devices and the equivalent masses (in relation with required power) of the source of power supply (for example, solar battery) in this case do not depend on the duration of the system operation. At the same time similar characteristic of control systems with propulsion engines increases with rise of the orientated flight. Furthermore, the required switching of propulsion engines increases, which leads to reliability lowering of system [1,2].

For the active spatial (triaxial) orientation of satellites by using the inertial devices different structures have been proposed; among them the use of three reaction wheels, installed along each connected axis, is the most natural. The operation of a simple wheel is shown in Fig. 1a: when the reaction wheel rotates by a motor in one direction, then the spacecraft, according to the law of conservation of the angular momentum, will rotate in the opposite direction. However, such architectures have relatively low quiescent power and are very inefficient in torque production [3]. The double and single gimbal Control Moment Gyroscopes (CMGs) are widely used to produce larger output torques. Unlike the reaction wheels, in which the spin axis are fixed to the satellite, these devices allow the rotors spin axis to rotate in the spacecraft reference frame using a gimbal mount [3,4] (Fig. 1b). For definiteness, assume that the axis of precession of the gyroscope coincides with the X-axis and that vector $\boldsymbol{H}$, in the initial position, lies in the plane of the orbit. Assuming the body of satellite as the outer frame, such a mechanical system forms a three-stage gyroscope. One of the properties of a three-stage gyroscope is the precession under the action of the external forces applied to it. This means that in order to create a control moment, it is sufficient to apply the torque of the motor-wheel $\boldsymbol{M}_{RW}$ to the precession axis of the two-stage gyroscope, under which the device will begin the precess with angular velocity

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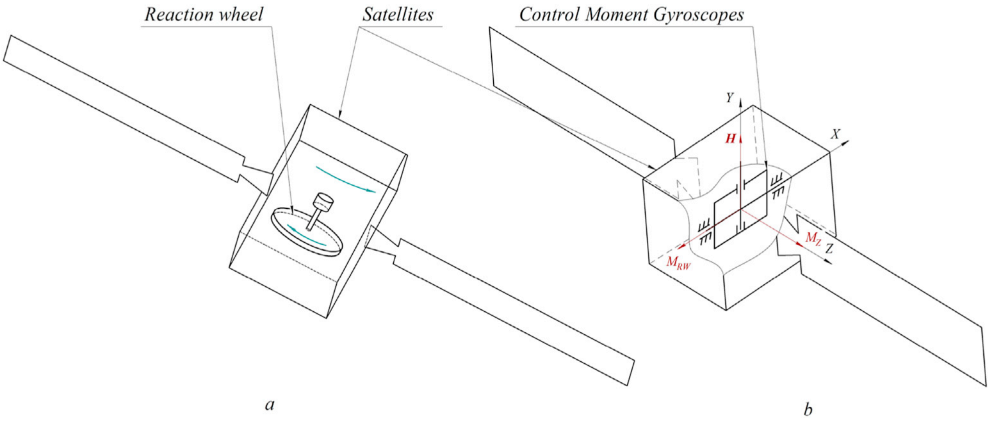

Fig. 1. Schematic representation of satellite orientation by a reaction wheel (*a*) and a control moment gyroscope (*b*).

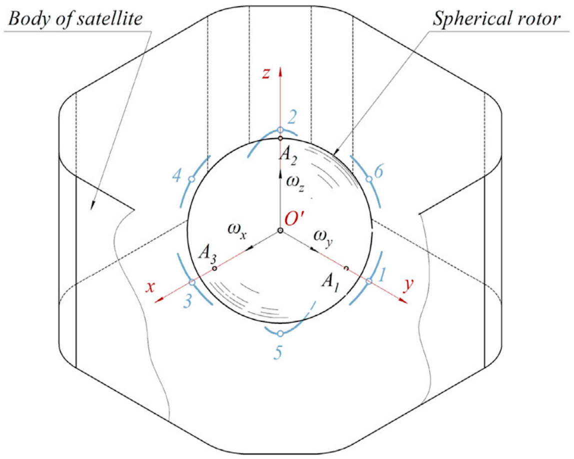

Fig. 2. Triaxial gyroscopic stabilizer with spherical rotor.

$$\dot{\upsilon} = \frac{\boldsymbol{M}_{RW}}{\boldsymbol{H}}. \tag{1}$$

These kind of mechanisms, also known as double gimbal CMGs, are usually complex and expensive. It is challengeable to design a double-gimbal CMG with reasonable and prudent structural mode frequencies and again limitation on torque production occurs. Single gimbal CMGs on the other hand, are mechanically simpler, but for producing torque around any arbitrary direction at least three CMGs are needed. The use of multiple CMG is also usual to avoid gimbal lock, and obtain large angular movement [5]. Although some authors [6–8] proposed (with some restrictions) designs with just two single gimbal CMG but these devices are still not appropriate for small satellites due to their heavy and relatively spacious structure (see, for example [9–11]).

An attractive method for creating the inertial moments is the concept of control moment gyroscopes with a spherical rotor. The concept consists of spinning a spherical body around its center (a point) and creating torques with any arbitrary velocity and direction by means of regulable actuators. This device has only one reaction mass so that it would be possible to considerably reduce the weight and volume compared to the conventional attitude control system. Such mechanism has several advantages over the above mentioned structures: their symmetrical shape allows to control the angular movements of the satellite simultaneously around the three axes; the spherical wheel is not gyroscopically connected to the body of the apparatus, and as a result, there is no gyroscopic relationship between the control axes in the control system and the wheel; advantage in weight and simplicity of structure. Although spherical wheels are considered as inertial actuators, which most fully satisfy the requirements imposed on the orientation and stabilization elements of space vehicles, especially those with a long life expectancy and requiring high accuracy of control [12], but they have not been applied widely in the practice for small satellites.

In what follows, we present a new improved concept of recently proposed two-degrees of freedom spherical reaction wheel [13] for triaxial orientation of small satellites. The Complete equations of motion of the satellite including the proposed stabilizer for numerical simulations and control law design are introduced. To provide robustness to the stabilizer a new control algorithm based on continuous high-order sliding mode algorithms for managing momentum and maintaining a torque attitude in the presence of perturbations/uncertainties is presented.

2. Model description and mathematical model

The proposed spherical moment gyroscopic stabilizer, referred here as a spherical stabilizer has a rotor in the form of a sphere, the geometrical and the mass center of which O' maintains motionless respect to the satellite (Fig. 2). The sphere can be driven by DC motors, magnetically, by piezoelectric actuators or by induction. The actuators are situated in the surfaces that pass through the point O' and are parallel to the coordinate surfaces of axes *Oxyz* (main axes of the satellite).

In Fig. 2 six arcs representing the actuators are conditionally pictured; arc pairs *1* and *4*, *2* and *5*, *3* and *6* create stators of three (or may be six) actuators which create the necessary moment on the sphere. The movement of the sphere is easier to be represented by projecting its angular velocity $\boldsymbol{\omega}_s$ on some coordinate system, for example with respect to the main satellite coordinate system *Oxyz* we obtain ω_x, ω_y, ω_z as it can be observed in Fig. 2.

If the inertia ellipsoid of the rotor, as it should be in the ideal case, is a sphere, therefore, the kinetic moment of the stabilizer can be described by

$$\boldsymbol{H} = I_s \boldsymbol{\omega}_s, \tag{2}$$

where I_s is the inertia moment of the rotor respect to any central axis. The bounded angular velocity of the sphere $||\boldsymbol{\omega}_s||$:

$$|\omega_x|, \quad |\omega_y|, \quad |\omega_z| \le \omega_{max}, \tag{3}$$

gives a region of summary kinetic moment variation S conformed as a cube with edges equal to $2I_s\omega_{max}$ parallels to axes *Oxyz*. This structure provides triaxial orientation of a satellite in space.

To justify this election we will use the parameter ρ, which defines the orderliness degree of linear velocity fields of moving bodies, estimated from the view point of effectiveness in creating the summary rotating impulse $H := \|\boldsymbol{H}\|$ [14]