DESIGN OF A REACTIONLESS POINTING MECHANISM FOR SATELLITE ANTENNAS

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ABSTRACT

In this paper, the design of a novel two-degree-of-freedom (DOF) reactionless pointing mechanism for satellite antennas that requires only the minimum number of actuators (i.e. two) is presented. At first, the basic concept and the theory of dynamic balancing are addressed. The balancing equations are derived by requiring that the mechanism centre of mass will remain fixed at a pivot point and that any reaction moments are internally cancelled. A typical example of a 20 kg antenna composed of of-the-shelf parts is used to study the mechanism properties. Simulation tests via the dynamic simulation software ADAMS are performed to verify the reactionless nature of the mechanism for arbitrary trajectories. The advantages and disadvantages of the pointing mechanism are discussed as well as the ability of extending the concept ideas to other satellite subsystems or even terrestrial applications.

1. INTRODUCTION

The growing threat generated by space debris is nowadays irrefutably confirmed. The collision of a defunct Russian satellite (COSMOS 2251) with the U.S. telecommunications satellite Iridium-33, which destroyed both of them, underlines the need of control and mitigation of this phenomenon. Terrestrial monitoring facilities, which worked properly in identification and forewarning of active satellites can no longer be considered satisfactory due to their limited resolution. Hence, the concept of in-situ (in-orbit) detectors comes to prevail over these limitations. The international space community lead by ESA's Space Situational Awareness (SSA) and NASA's Space Based Space Surveillance (SBSS) programs has already set the research's guidelines. In order to meet the requirements of in orbit space debris tracking, radar systems capable of being attached directly to pathfinder satellites have to be developed.

However no such tracking system would help alleviate the problem if it would induce disturbances in the base satellite itself. Indeed, all antenna actions would force the satellite's Attitude Control System (ACS) to compensate the resulting dynamic reactions by using jet thrusters and momentum exchange devices. Since the latter require occasional de-spinning, achieved by thrusters firing, eventually all dynamic disturbances on a spacecraft require the use of thrusters and consequently the expenditure of fuel. Because thruster fuel is a limited resource in space, such disturbances reduce a space system's life span, until its final decommission at which point one (at least) more space debris would result, thus causing a vicious circle. Consequently, the effort for space based space debris monitoring should be combined with the development of reactionless mechanisms capable of blocking reactions to their base.

Apart from space debris tracking devices, any kind of accelerating or rotating appendages connected to a free-flying base through a joint, necessarily transmits reaction (or shaking) forces and moments to their base, disturbing it from its orientation and position, and generating undesirable vibrations. This situation is even encountered when solar panels must move to track the sun, while the rest of the structure must remain at a constant attitude. Also, a moving manipulator on a space structure or satellite transmits reaction forces and moments that disturb the position and orientation of the structure and can have adverse effects to the structure's microgravity environment. As a consequence, increasing a system's useful life and reducing its cost partly depends on the minimization or elimination of reaction-induced disturbances. Additionally, such disturbances elongate mission time due to the need for corrective maneuvers, and increase the cost for putting a satellite or other spacecraft in orbit due to the weight of the additional fuel needed. These observations lead to the conclusion that elimination of the dynamic reactions is an important design and operational consideration for satellites and other structures in general.

One method for achieving the goal of minimum appendage-induced disturbances is to design and employ a *reactionless* mechanism. Towards the realization of zero force/ moment reaction mechanisms, two main methods have been proposed: (a) *by path planning* and (b) by *design (by mechanical means)*, while there is some work based on the combination of the two [13]. Such mechanisms have been proposed for serial manipulators and for closed-chain mechanisms, such as four-bar mechanisms.

By using zero-reaction path-planning, a mechanical system is moving along a trajectory, in a way that keeps the total system momentum constant. This technique relies upon the existence of more than one base-mounted actuators. Then, the manipulator moves in such a way that the base actuator torques cancel each other. However, generation of suitable trajectories is complicated due to the coupling of the mechanism dynamic equations. It has been shown, though, that these can be decoupled and the inertia matrix rendered invariant for a class of planar manipulators, resulting in significant simplifications to the problem [2, 19]. The main task then is to select the mechanism kinematic and inertial parameters so as to obtain practical reactionless trajectories.

In the case of a single actuator at the base, the Enhanced Disturbance Map was proposed, in which the motion of the mechanism in certain trajectories, results in zero disturbances on the base [7]. The method does not apply to any desired trajectory. Reducing manipulator reactions by cost function minimization was also proposed [15], as well as the method of the Reaction Null Space trajectory planning, where the joint rates are calculated using null space properties, [11, 12]. A basic disadvantage of these methods is the luck of robustness due to the risk of running the mechanism into singularities or the inability to move towards a required point without unwanted reactions on the base.

On the other hand, regarding the zero-reaction designs, several ideas have been proposed, both for serial and parallel mechanisms [1], as well as for planar [9] and three-dimensional mechanisms [3, 8, 16]. Other approaches generalizing the shaking force minimization and elimination techniques can be found in references [4, 14, 17], while reference [16] tackles the problem of spatial linkage balancing.

The design and testing of a number of reaction force balanced mechanism prototypes has been discussed in [5, 10]. The nature of these manipulators is passive, as far as the shaking force is concerned. Shaking force elimination is accomplished by fixing the centre of mass (CM) of the mechanism via the use of counterweights. Furthermore, minimization of the rocking moment is accomplished by introducing a counteracting torque. However, this is generally done using an additional and oppositely rotating actuator attached to the base and with a preset inertia [16]. For space systems, the use of gyroscopic effects via Control Moment Gyroscopes (CMGs) has also been proposed for the elimination of reaction moments [6].

In this paper, the design of a novel two-degree-of-freedom (DOF) reactionless pointing mechanism for satellite antennas that requires only the minimum number of actuators (i.e. two) is presented. The basic concept and the theory of dynamic balancing are addressed. The balancing equations are derived by requiring that the mechanism CM will remain fixed at a pivot point and that any reaction moments are internally cancelled. A typical example of a 20 kg antenna composed of of-the-shelf parts is used to study the mechanism properties. Simulation tests via the dynamic simulation software ADAMS are performed to verify the reactionless nature of the mechanism for arbitrary trajectories. The advantages and disadvantages of the pointing mechanism are discussed, as well as the ability of extending the concept ideas to other satellite subsystems or even terrestrial applications.

2. DYNAMIC BALANCING

The present work focuses on the design of zero force/ moment reaction passive mechanisms, since they are capable of achieving the goal without restricting the trajectory of the mechanism or running the risk of not being able to avoid singular configurations. Moreover, this is achieved by a novel mechanism design that exploits the dynamic balancing theory and accomplishes both force and moment cancellation, without the need for additional actuation.

To demonstrate the concept of dynamic balancing theory, consider a fixed mass system (e.g. an antenna). The sum of all external forces acting on it is equal to the rate of change of its momentum, while the sum of all external moments acting on it (with respect to a fixed point) is equal to rate of change of its angular momentum (with respect to the same point), namely:

$$\sum \mathbf{F} = m\dot{\mathbf{v}}_{CM} \tag{1}$$

$$\sum \mathbf{M}_0 = \dot{\mathbf{h}}_0 \tag{2}$$

where $\Sigma\mathbf{F}$ is the sum of all external forces acting on the mechanism, m is the mechanism's total mass, $\mathbf{v}_{CM}$ is the velocity of its CM, $\Sigma\mathbf{M}_o$ is the sum of all external torques acting on it with respect to fixed a point O and $\mathbf{h}_o$ is the angular momentum of the mechanism, with respect to the same point. Due to the action-reaction principle, the opposite of the right-hand side terms in Eqs. (1) and (2) represent the reaction forces/ moments (or shaking forces/ moment) applied by the moving mechanism to the space vehicle base, through its mounts.

Eqs. (1) and (2) show that, if the mechanism momentum ($m\mathbf{v}_{CM}$) and its angular momentum ($\mathbf{h}_o$) remain constant for any motion at all times, then the reaction forces/ moments will be equal to zero. Hence, two constraints have to be satisfied for a system-mechanism to be reactionless:

$$\dot{\mathbf{v}}_{CM} = 0 \Rightarrow \mathbf{v}_{CM} = const. \tag{3a}$$

$$\dot{\mathbf{h}}_0 = 0 \Rightarrow \mathbf{h}_0 = const. \tag{3b}$$

If the mechanism is initially still, then the constant quantities on the right-hand side of Eqs. (3) are zero. Thus, integrating Eq. (3a), the following is obtained:

$$\mathbf{r}_{CM} = const. \tag{4}$$

i.e., the moving mechanisms' CM must be kept still. Eq. (3b) and (4) are necessary and sufficient conditions for a mechanism to be dynamically balanced i.e. reactionless. Note that if these conditions are met approximately, then the reaction forces and moments are not zero, but are small. This allows for flexibility in designing reactionless systems.

To illustrate the above concept, consider a one DOF pointing mechanism, see Fig. 1, in which a rod of length r_b with a point mass m_b (antenna) at one end rotates about its pivot (point O). A shaking force and a shaking moment will act on the frame whenever the mass accelerates or decelerates. However, if dynamic balancing conditions are imposed, reactions can be eliminated. Regarding the cancellation of the reaction forces, a counterweight of mass m_c at a distance r_c from the mounting point is added, in such a way that the total mechanism CM is kept fixed at the mounting point O. To cancel the reaction moment, a possible solution would be to add a wheel of inertia I_c, rotating contrary to the rotation of the mechanism, in such a way that the system total angular momentum is kept equal to zero. Thus, from Eq. (3) and (4), the following is obtained:

$$m_b r = m_c r_c \tag{5}$$

$$I_c = m_b r_b^2 + m_c r_c^2 \tag{6}$$

If the constraints given by Eqs. (5) and (6) are observed, then pairs of reaction forces that are canceling each other are created ($F_{bx} = F_{cx}$, $F_{by} = F_{cy}$ and $T_d = kF_{cx}$), see Fig. 1.

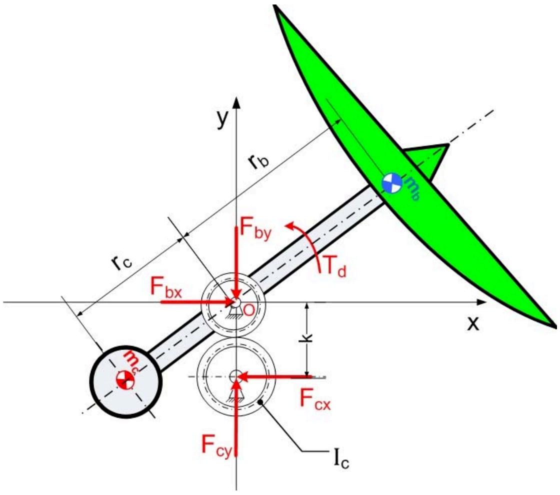

Figure 1. Concept representation of a dynamically balanced system (not in scale).

Although this technique eliminates reactions, the need for an additional actuator is introduced for the motion of the inertial wheel. This makes the system more complicated, since it includes additional electromechanical parts and additional sensors and controls, all subject to failures. To avoid such effects, solutions requiring additional actuation are dismissed. Instead, the novel reactionless pointing mechanism proposed, does not need additional actuation.

3. CONCEPTUAL DESIGN

To implement the mechanism some specifications dealing with the nature of the motion and the formation of the structure must be taken into account. As far as the nature of the motion is concerned, this is prescribed to be a zero reactions 2 DOF pointing motion, in order to point the antenna -and track the debris- while at the same time the mechanism's base (and the satellite therefore) should not suffer of any disturbances. Furthermore, this motion must be accomplished with the minimum number of actuators (reaction suppression should be achieved passively).

Taking into account these restrictions, a novel mounting and pointing mechanism of the antenna is proposed, see Fig. 2, 3.

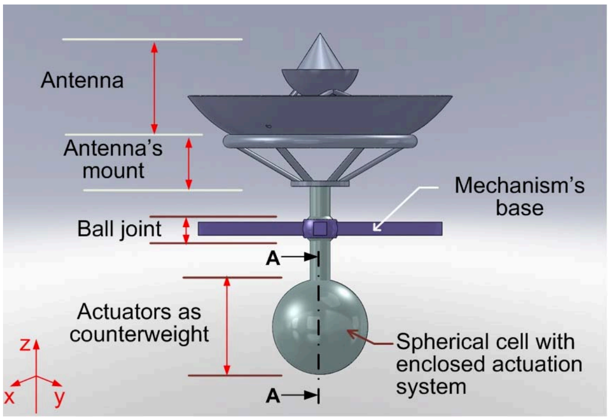

Figure 2.Three-dimensional CAD model of the conceptual design.

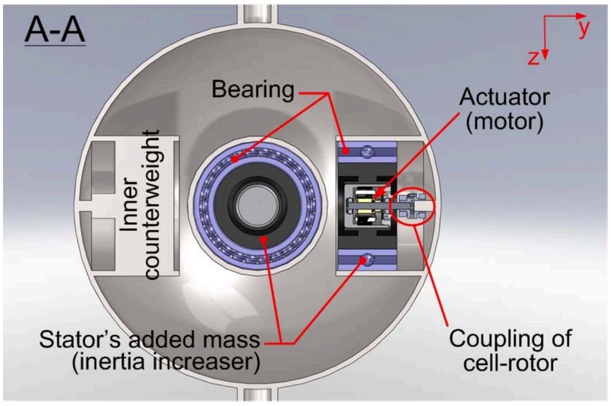

Figure 3. Section of the actuation system.

The mechanism consists of two rods sharing the same axis and mounted on opposing sides of a ball-and-socket joint. The antenna is mounted at the free end of one of the rods, while a counterweight is mounted at the free end of the other rod. The counterweight is a spherical cell containing the antenna actuation mechanism, eliminating thus the need for additional mass.

3.1 Actuation system

The actuation mechanism consists of two rotational actuators along axes x and y, used for pointing. Each actuator is connected via coupler to a small shaft, fixed on the spherical shell, see Fig. 3.

When the rotor of an actuator rotates, the spherical shell receives a moment. This moment results in the rotation of the system around its CM at the centre of the ball joint, thus moving the antenna along an arc-trajectory around that point. Coordinated motion of the two actuators results in the motion of the antenna along any trajectory in spherical coordinates, thus enabling accurate pointing.

The actuators are gimbaled. In addition, the stator of each actuator is not fixed, but instead is left to rotate freely. Ball bearings between the stator and the cylindrical shell inside the spherical cell, enable the stator to stay in position, while rotating freely.

In this way, the rotor applies the desired torque to the shaft and therefore accelerates the antenna, while a relative motion between the rotor and the stator is possible, see Fig. 4. To keep the stator acceleration at reasonable levels, its inertia must be selected with care and in accordance to Eq. (6).

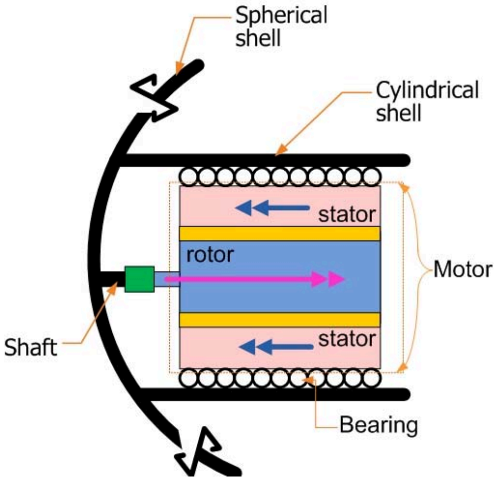

Figure 4. Actuation system principle.

3.2 Balancing CM

Having described the mechanism, its reactionless properties can now be explained. Regarding the reaction forces, their elimination is achieved by keeping the mechanism CM fixed at the centre of the ball joint, (non-actuated), see Fig. 5, using the counterweight containing the actuation mechanism itself, in consistence with Eq. (5) i.e.:

$$2\times\left[\left(m_m + m_I + m_b\right) + m_{cw}^{in}\right] r_m + m_s r_s = m_a r_a \qquad (7)$$

where m_m is the mass of the actuator rotor, m_I is the total mass of the actuator stator (and its additional inertia), m_m is the bearing mass, m_{cw}^{in} is the mass of the inner counterweight, m_a is the antenna mass and m_s is the mass of the rest of the structure. Also, r_m, r_a are the lengths of axes between the antenna CM, the actuation system CM and the centre of the ball joint respectively. In this way, no excessive mass is required for the counterweight, thus minimizing the mechanism total mass.

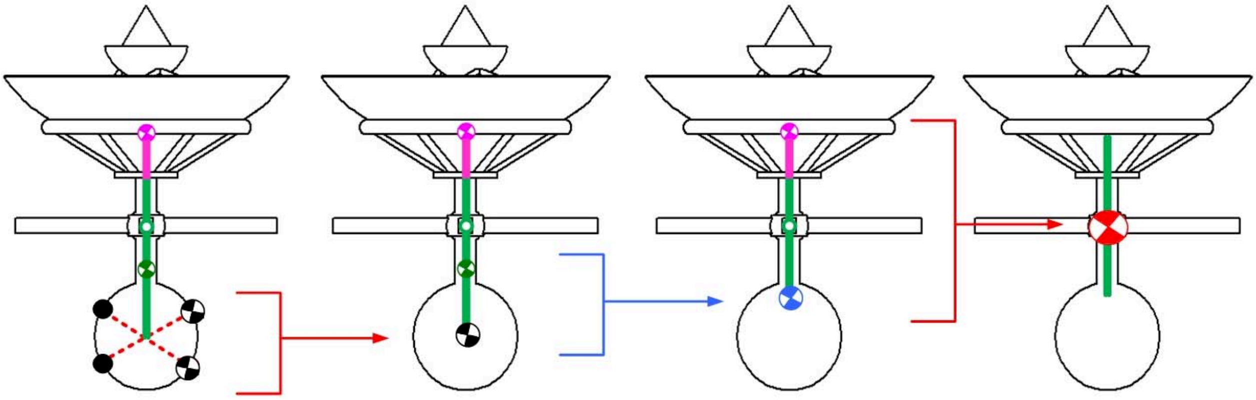

Figure 5. Balancing of antenna substructure CM.

Regarding the reaction moments, their elimination is achieved by the use of the ball joint as a mounting mechanism of the antenna blocking moment transmission to/ from the antenna's base. Torques are produced by the actuators but these are counteracted internally in the counterweight due to the special actuation principle employed. Thus, no additional actuation is needed to counter reaction moments, since the latter do not exist.

4. SIMULATION RESULTS

The verification of the reactionless nature of the proposed pointing mechanism is performed using the multibody dynamics simulation software ADAMS. At first, realistic parameters are selected for each component of the mechanism. Namely, the antenna design follows the previously used High Gain Antennas (HGAs) with a focal length/ diameter ratio (f/d) of 0.33 and reflector diameter equal to 1m, thus having a mass of 20.1kg. Mass and inertia properties given in Table 1 for all parts were exported from CAD software and applied to the corresponding ADAMS model.

Table 1. Subsystem inertial parameters.

Part	Parameters	
Antenna	mass [kg]	20,1
	inertia [kgmm^2]	Jx=Jy=1,9•10^6, Jz=1,3•10^6
Remainder structure	mass [kg]	10,775
	inertia [kgmm^2]	Jx=Jy=5,7•10^5, Jz=1,8•10^5
Rotor	mass [kg]	0,20
	inertia [kgmm^2]	Jx=Jy=144,5 Jz=10,0
Stator	mass [kg]	4.0
	inertia [kgmm^2]	Jx=Jy=5,4•10^3, Jz=4,7•103
Bearing	mass [kg]	0,85
	inertia [kgmm^2]	Jx=Jy=1,2•10^3, Jz=1,064•10^3

4.1 Simulations Runs

Simulation runs have been performed for several arbitrary trajectories. The results obtained for a time interval of 30s are presented. The assigned profile of actuation torques along axes x, y -same for both DOFs,- is shown in Fig. 6. Under this actuation scheme the mechanism's model moves with constant acceleration during the start phase for 10s, is rotated with a constant cruise velocity for another 10s, and is decelerated for the rest of the time with constant deceleration, thus generating a trapezoidal velocity profile for each DOF, see Fig. 7.

Reaction forces and moments calculated at the pivot point (and thus the supporting base) are depicted in Figs. 8, 9 respectively. The results clearly demonstrate that the reaction torques are identically zero and reaction forces are infinitesimally small ($<10^{-9}$ N), hence, the main body of the space vehicle will not suffer any disturbances even when accelerations change abruptly, such as ta times 10 s and 20 s.

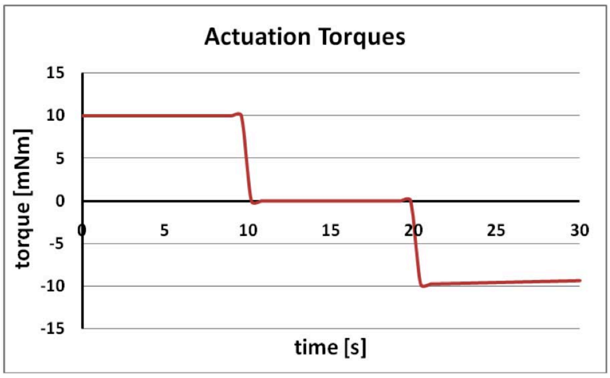

Figure 6. Assigned profile of actuation torques.

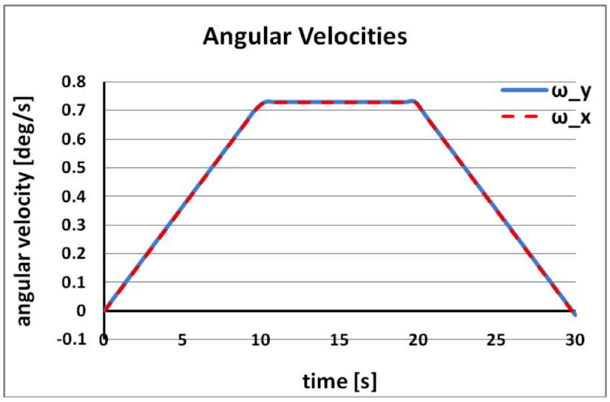

Figure 7. Generated angular velocities around x,y axis.

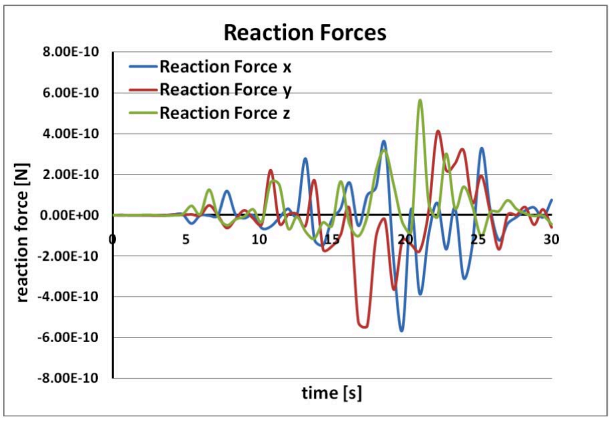

Figure 8. Reaction forces on base.

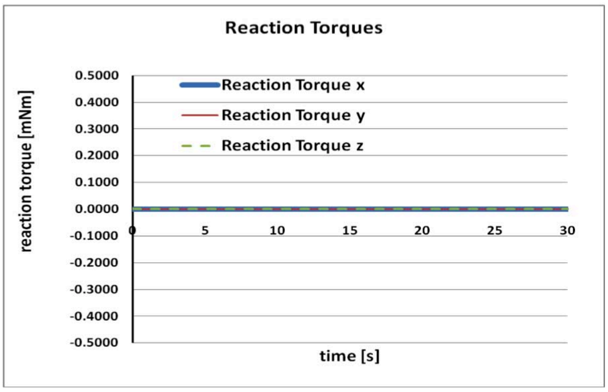

Figure 9. Reaction moments applied to the base.

4.2 The Self-spinning Phenomenon

A side phenomenon occurring during coordinated motion of antenna is the rotation of the latter around its symmetry axis. This is a gyroscopic phenomenon due to the dynamic coupling of the angular velocities arising from the antenna Newton-Euler equations of motion:

$$\mathbf{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega}^{\times}\mathbf{J}\boldsymbol{\omega} = \boldsymbol{\tau} \tag{8}$$

where $\mathbf{J}$ is the mechanism inertia matrix, $\boldsymbol{\omega}$ is the antenna angular velocity vector, $\boldsymbol{\tau}$ is a vector containing the applied (actuation) torques and $(\bullet)^{\times}$ applied to a vector yields the antisymmetric cross product matrix.

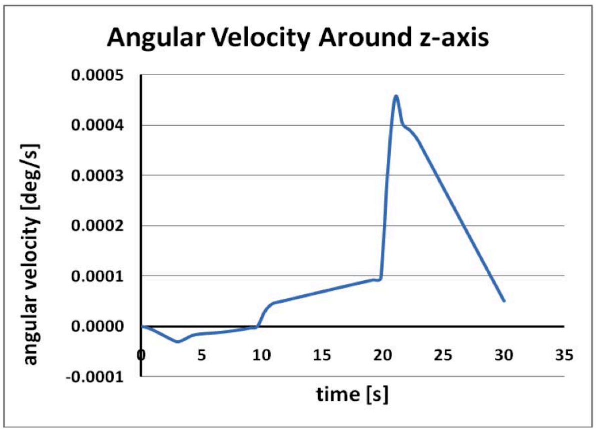

Figure 10. Angular velocity around symmetry axis.

This resulting rotation about the antenna axis of symmetry (z-axis), see Fig. 10, has no significance, since most satellite antennas are axisymmetric and therefore no such motion would affect their orientation. However, if self-spinning is considered to be undesirable a few solutions can be proposed, the simplest of whom would be the mounting of the antenna via a cylindrical joint at the intermediate of it and the rod.

5. DISCUSSION

The design described above has been developed in context of reactions rejection for satellites antennae. In order to realize the proposed design some tradeoffs must be taken into account. At first, the reactionless property is concerned, which consist the basic alteration with the pointing mechanisms currently in use. Full reactions suppression is achieved by passive mechanical means, thus increasing the robustness of the system. Furthermore, note that each inner counterweight in Fig. 3, can be replaced by an additional motor controlled by the same reference. In this case, the robustness is increased since each DOF is actuated two smaller motors and thus redundancy is achieved. In the case of failure of a motor, the other motor can be used to point the antenna more slowly. Also, the use of the actuators as antenna counterweights is an advantage compared to passive mechanisms currently proposed, since the total mass is minimized. In general, the pointing mechanism consists of existing components assembled in an idiomorphic way, providing distinct benefits over classical designs.

5.1 Mounting requirements

Regarding the mounting of the mechanism, some considerations must be made. The pointing system requires a special mount due to the counterweight. However this need can be overcome in new satellites, by proper design of the mount. The ball joint offers maximum feasibility while blocking any moments. As far as its suitability for a space mechanism is concerned, this design can be substituted by a gimbaled design where the joint is made of simple revolute joints with axes intersecting at a common point.

5.2 Possible extensions

The mechanism is designed for antenna pointing but the concept ideas can be extended easily to other satellite subsystems. For example, it can be used in solar panel rotation mechanisms that readjust panel orientation, to achieve maximum power efficiency. In fact, the symmetric nature of solar panels structure offers the benefit of having their global CM located at the rotation axis. Hence, implementation of the proposed mechanism in solar panels can deliver sufficient performance, without disturbing the orientation of the satellite and without requiring the counterweight. Also, the mechanism can be beneficial for thruster pointing and payload mechanical support. Space construction by telemanipulated or autonomous mechanisms are also candidate applications, since the design can enhance the performance and the quality of the tasks by minimizing perturbations. Additionally, various exploration missions, which employ moving mechanisms, such as planetary orbiters or surface platforms, can also benefited.

Aside from space applications such a mechanism can also implemented in terrestrial applications. Indeed, it can be used in applications where minimal perturbations are of particular interest, such as in telemanipulated surgery, ship radars, telescope mechanisms, industrial applications requiring high accuracy, etc.

6. CONCLUSIONS

The design and dynamic balancing of a novel reactionless antenna pointing mechanism has been presented. A design strategy where actuators mass is used as counterweight and an actuation scheme where the motors are gimbaled and left to rotate freely were used to dynamically balance the mechanism. The balancing equations have been derived by imposing that that the global CM mass is fixed at a pivot point exactly at the centre of a spherical joint and that the reaction rotations are internally cancelled. Using CAD models and the dynamic simulation software ADAMS the motion of the prototypal pointing mechanism was simulated for various pointing trajectories. Typical simulation results given in this paper show that the mechanism transmits no reaction forces to the antenna base. The advantages of the proposed mechanism have been synopsized, while the special requirements have been tackled. Finally, possible extensions of the basic concept to other applications have been discussed.

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