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Closed-loop magnetic bearing and angular velocity control of a reaction sphere actuator

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ABSTRACT

This article presents the first closed-loop magnetic bearing and angular velocity experimental results of a reaction sphere actuator for satellite attitude control. The proposed reaction sphere is a permanent magnet spherical actuator whose rotor is supported by magnetic bearing and can be torqued electronically about any desired axis. The spherical actuator is composed of an 8-pole permanent magnet spherical rotor and of a 20-pole stator with electromagnets. The electromechanical model of the reaction sphere is summarized together with procedures to estimate the rotor magnetic state, the back-EMF voltage, and the rotor angular velocity, which are all fundamental ingredients for controller design. Dynamic controllers are developed to levitate the rotor inside the stator (magnetic bearing) and to control the rotor angular velocity. The magnetic bearing is based on a state-space controller with reduced-order displacement velocity estimator whereas the angular velocity controller is a simple proportional controller with a dedicated angular velocity estimator. The developed control algorithms are experimentally validated using the developed laboratory prototype showing the ability of simultaneously levitating the rotor while rotating it about a given arbitrary axis.

1. Introduction

Attitude Determination and Control System (ADCS) is among the main satellite subsystems and is responsible to stabilize the vehicle and orient it in desired directions during the mission despite external disturbance torques acting on it [1]. A three-axis stabilized spacecraft actively controls the inertial position of all the three axes. Momentum exchange devices are common actuators used for three-axis attitude stabilization and maneuvering and include Reaction Wheels (RWs) and Control Moment Gyroscopes (CMGs) [2]. With CMGs (used in manned spacecraft) torques of 200 Nm are achievable. However, such CMGs are very heavy and are seldom used in the ADCS of ordinary-sized satellites [2]. For very accurate attitude control systems and for moderately fast maneuvers, the RWs are preferred because they allow continuous and smooth control of torque with the lowest possible parasitic disturbing torques. The level of torques that can be achieved with RWs is of the order of 0.05–2 Nm [2]. For three-axis control, three orthogonal RWs, with each one's rotational axis parallel to one of the spacecraft body axes, make up the simplest control system. However, a four-wheel pyramid scheme is installed in order to increase the reliability of the entire system, with the spin axes o each wheel pointing normal to the faces of a pyramid. This configuration provides redundancy as well as greater flexibility in the distribution of wheel angular momentum [2].

Rotor bearings of momentum exchange devices include mechanical and magnetic bearings. In the space environment of subpressure, lubrication of (mechanical) ball bearings is a major problem that has not been completely solved. Moreover, the ball bearing suffers from excessive friction loading. In recent years, the development of magnetic bearings has taken a decided upturn, with good prospects for the future [2]. Magnetic bearings improve the torque-to-noise ratio by eliminating the parasitic torque noises characteristic of ball bearing [2,3].

Multi-axis momentum exchange devices capable of producing torque in any direction have also been proposed. The idea behind these devices is to provide a compact solution for three-axis attitude control by combining the four-wheel scheme in a unique actuator. A fully active magnetic bearing wheel with five actively controlled axes is presented in [3]. The wheel can be actively tilted by $\pm 1.7^{\circ}$ enabling to use it simultaneously as a RW and CMG. This enables three-axis attitude control of the spacecraft with only one wheel.

In line with these efforts, reaction spheres (RSs) were proposed more than 50 years ago, in 1960, three years after the launch of

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Sputnik 1 [4,5]. The leading idea was to replace the three rotating masses of RWs by a single spherical (hollow) mass, which can be torqued about any direction to provide three-axis attitude control with a unique device. For the suspension of the rotor, magnetic [4,6] and electrostatic [5,7] means have been proposed. Then, three induction motor stator windings in orthogonal planes export the requested torque to provide attitude control of the spacecraft about any axis. Twenty years later, in 1986, Isely patented the idea of a single magnetically supported torqued RS [8]. The rotor comprises a massive spherical body that is both electrical conductor an a magnetizable material whereas the stator is composed of three pair of mutually orthogonal windings. The forces acting to produce the torque result from the interplay of eddy currents, induced in the sphere by the magnetic flux of the centering winding, reacting with fluxes produced by the torquing winding. More recently, Doty proposed a RS concept consisting of an electromagnetic stator that surrounds a spherical conductive rotor [9]. In one embodiment, the stator includes twenty iron-core electromagnets arranged to form the shape of a truncated icosahedron around the spherical rotor, which is a hollow copper sphere.

A reaction sphere is a valuable alternative to a four-wheel configuration for spacecraft attitude control. However, none of the presented designs or concepts have reached the technology readiness level needed for a commercial product. The difficulty is in the three degree-of-freedom (3-DOF) motor, the bearing, and its combination. Recent advances in simulation and modeling, power electronics, sensing, and especially in high-power space-qualified processors give a totally new chance to the concept.

We have proposed a RS supported by magnetic bearing as a potential alternative to traditional momentum exchange devices such as RWs or CMGs [10]. The sphere can be accelerated in any direction by a 3-DOF motor making all the three axes of the satellite controllable by just a single device without the friction of rotating mechanical joints. A schematic illustration of the RS actuator is depicted in Fig. 1. The 3-DOF motor is synchronous and has permanent magnets (PMs) and electromagnets placed at the vertices of regular polygons. The PM motor is composed of a rotor with 8 poles and a stator with 20 air-core electromagnets, each corresponding to one vertex of a dodecahedron.

Reaction spheres can be classified into the family of spherical actuators, which are devices capable of performing 3-DOF rotational motion in a single joint. Spherical actuators are especially presented in the robotic literature, where researchers investigate new solutions to design compact and high performance 3-DOF rotary actuators [11]. A variety of different designs have been proposed in the last five decades. In general, the proposed designs consist in a rotating spherical rotor enclosed in a stator. Then, a mechanical shaft emerges from the rotor to export the torque. Although ultrasonic and piezoelectric spherical drives have been developed [12–14], electromagnetic devices are the most common and have attracted the attention of several research groups and industries throughout the world [15–24]. A literature review of these kind of actuators including their architectures and working principle can be found, for instance, in [11,25]. As it will be seen throughout this article, although aiming at a different application, the study of electromagnetic modeling and control aspects of the proposed reaction sphere shares many challenges and related techniques with the spherical actuator literature.

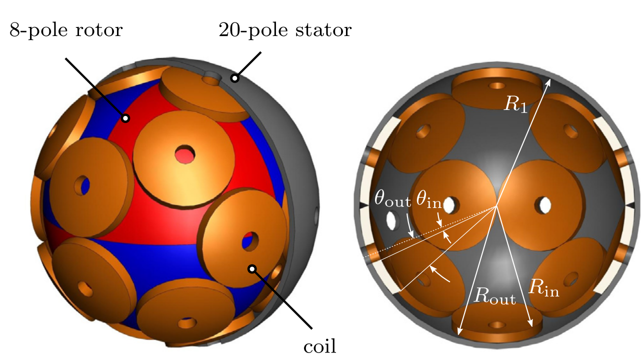

Fig. 1. Schematic illustration of the reaction sphere actuator with an 8-pole spherical rotor and a 20-pole stator. (Left) Only half of the stator is shown. (Right) Schematic of a half stator with coils.

In this article we present the first closed-loop experiments performed using the developed RS actuator prototype. In Section 2 we describe the working principle of the proposed actuator and present our previous work and related literature. Specifically, we introduce the developed laboratory prototype and summarize results from our previous research including the dynamic and kinematic models, the magnetic flux density model, the force and torque models, the magnetic state estimation procedure (determination of magnetic orientation), the rotor position determination technique, and the estimation of the back-EMF voltage and angular velocity of the rotor, which are all necessary ingredients for closed-loop controller design. Then, in Section 3 we present the control scheme and the design of magnetic bearing and angular velocity controllers. These dynamic controllers are based on classical approaches, and the main objective is to combine elements presented in Section 2 to prove the feasibility of closed-loop control. Finally, in Section 4 we report and discuss the experimental results.

2. Working principle of the reaction sphere

The RS is a PM synchronous spherical actuator whose rotor is magnetically levitated and can be accelerated about any desired axis. To guarantee mechanical and magnetic symmetries, rotor and stator poles were positioned following the vertices of regular polyhedra [25]. As depicted Fig. 1, a cubic (8-pole) distribution was selected for the spherical rotor, which is divided into height quarters, each of them being either a north pole if $xyz > 0$ or a south pole otherwise. An 8-pole arrangement was also considered by Ninhuijs et al. for their spherical PM gravity compensator [26,27]. Then, 20 air-core electromagnets were arranged on the stator following the vertices of a dodecahedron (20 vertices), which are necessary to avoid unwanted singular configurations [25]. Finally, notice that these 20 electromagnets are simultaneously employed to levitate the rotor inside the stator (magnetic bearings) and, at the same time, to generate the appropriate torque about any desired axis.

2.1. Laboratory prototype

A first RS laboratory prototype was manufactured to validate the force and torque analytical models [28]. In this prototype, the eight PM poles of the spherical rotor were discretized using a mosaic of 728 cylindrical magnets to approximate the desired fundamental spherical harmonic. More recently, a new spherical rotor optimized to improve its manufacturability was designed and manufactured [25]. As illustrated in Fig. 2 (left), the rotor has eight PM poles, which have truncated spherical shape and are parallel-magnetized. In Fig. 2 (right) we display one half stator composed of a hemispherical shell manufactured with Acrylonitrile Butadiene Styrene (ABS) material and 10 air-core coils, which have been manufactured with the desired spherical shape. Moreover, the stator is equipped with a total of 12 ABS cells, which besides protecting the coils, they also support magnetic flux density sensors necessary to compute force and torque models for any possible orientation of the rotor (see Section 2.5 below). There are several advantages using a non-magnetic stator including the