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Verification of Spin Magnetic Attitude Control System using air-bearing-based attitude control simulator

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ABSTRACT

This paper accomplishes one goal and it was to verify and to validate a Spin Magnetic Attitude Control System (SMACS) program and to perform Hardware-In-the-Loop (HIL) air-bearing experiments. A study of a closed-loop magnetic spin controller is presented using only magnetic rods as actuators. The magnetic spin rate control approach is able to perform spin rate control and it is verified with an Attitude Control System (ACS) air-bearing MATLAB® SIMULINK® model and a hardware-embedded LABVIEW® algorithm that controls the spin rate of the test platform on a spherical air bearing table. The SIMULINK® model includes dynamic model of air-bearing, its disturbances, actuator emulation and the time delays caused by on-board calculations. The air-bearing simulator is employed to develop, improve, and carry out objective tests of magnetic torque rods and spin rate control algorithm in the experimental framework and to provide a more realistic demonstration of expected performance of attitude control as compared with software-based architectures. Six sets of two torque rods are used as actuators for the SMACS. It is implemented and simulated to fulfill mission requirement including spin the satellite up to 12 $\mathrm{deg\,s^{-1}}$ around the *z*-axis. These techniques are documented for the full nonlinear equations of motion of the system and the performances of these techniques are compared in several simulations.

1. Introduction

The Attitude Control System (ACS) cannot be fully verified in real conditions before flight. The main reason is that the hardware on ground cannot be submitted to the real flight conditions and environment. Therefore during the ACS verification process, a complete and careful step by step verification logic from numerical models to real hardware is carried out in order to validate the behavior of the ACS. The use of Hardware-In-the-Loop (HIL) spacecraft attitude control system simulator or air-bearing is a very promising approach which may increase the reliability of the tests. This simulator also offers an alternative to digital only verification of control system software. In fact an air-bearing based flight dynamics simulator is an important part of an overall process for developing and testing attitude control system algorithms.

Spin Magnetic Attitude Control System (SMACS) in particular is used when it is important to have low-cost and low-mass control system. Principal methods of SMACS are considered in [1–6]. General dynamical properties of a spin-stabilized satellite along with technical issues are discussed in [7–9]. Attitude control techniques for satellites are rapidly accumulating in the literature but relatively few experiments exist for verification, in particular simulator-based verification. A fault-tolerant sliding mode attitude control algorithm for a nano-satellite has been developed in [10] and they used air-bearing table for performing tests. An air-bearing table has also been utilized for attitude control development in [11,12] in their work also proposed a tiled wheel for generate torques in all three principal axes of a rigid satellite and a full air-bearing platform was undertaken for experimentally validate the actuator.

An experimental verification of modern and classical attitude control laws on flexible structures was done at flexible spacecraft simulator at the Naval Postgraduate School [13]. Polo et al. [14] have presented an end-to-end validation process for the Instituto Nacional Tecina Aeroespacial (INTA) Nanosatellite-1B three axes attitude control. The validation environment combines a Flat Satellite configuration and a real time emulator working in closed-loop. Special equipment has developed in ZARM for demonstration

Acronyms and abbreviations: ACS, Attitude Control System; SMACS, Spin Magnetic Attitude Control System; HIL, Hardware-In-the-Loop; LEO, Low Earth Orbit; rpm, revolutions per minute; AHRS, Attitude and Heading Reference System

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and laboratory testing of Tahiti Nui Satellite (TNS-0) motion identification and control algorithms [15]. The facility consists of a horizontal smooth table and mobile mock-up that enables to glide over the table surface owing to compressed air stored in on-board pressure tanks. On-Orbit system identification is a supplementary approach for validation of attitude control system. The Zhejian University Satellite (ZDPS-1A) mission was on-orbit system identification and the realization of nadir pointing three-axes stabilization was verified by on-orbit results [16]. Paper [17] is a comprehensive survey of works on verification of a high spin rate magnetic controller for Estonian Student Satellite (ESTCube-1). The algorithm was tested in a simulation environment and hardware-in-the-loop test was also performed to verify on-board software.

The SMACS is an attractive means of generating control torques for many Low Earth Orbit (LEO) satellites. This system can result in significant weight reduction for long mission because it is not dependent upon the length of the mission. Moreover, magnetic control proves to be a challenging problem as magnetic actuators do not provide three independent control torque components at each time instant. Incidentally, the SMACS offers potentially great reliability than other systems. However, this reliability potential can be realized only if the controller can be verified by the use of HIL simulator. Therefore in this paper a very strict proof of verification is derived for a magnetic control law that leads the satellite to a desired spin rate around a principal axis of inertia. Magnetic torque rods are used to produce external torques on the satellite by acting against Earth's local magnetic field without using Helmholtz coil for producing a region of nearly uniform magnetic field [18]. This research verifies SMACS with an ACS air-bearing MATLAB® SIMULINK® model and a hardware-embedded LABVIEW® algorithm that controls the spin rate of the test platform on a spherical air bearing table. The analytical simulation and experimental results are then compared to examine the applicability of the presented controller in real hardware and it is also important to be able to show that the nonlinear simulation results accurately predict the platform results. Consequently, the numerical precision of the on-board computer will be represented and compared to analysis or simulations performed during air-bearing experiments.

2. Air-bearing simulator

The air-bearing is a table-top-style bearing that can support a 300 lb payload, shown in Figs. 1 and 2. The platform floats on a thin cushion of air, allowing the spherical surface to rotate with little to no friction. Compressed air is dried, filtered, regulated down to approximately 2 psi, and fed up through the pedestal and into the air bearing system. This system can tilt $\pm 30°$ from the horizontal and spin freely about the vertical (yaw) axis. Attitude control options include four reaction wheels and twelve magnetic torque rods capable of producing a dipole moment of 10 A m^2. In this research magnetic rods have just used as actuators. The magnetic rods performance data has presented in Table 1. Hardware located on the air-bearing includes a torque rod driver circuit board, a flight computer (PC/104), batteries, power supply, remote communications equipment and AHRS (Attitude and Heading Reference System) for attitude determination. The table is coarsely balanced by automatically and manually adjusting the position and mass of lead screws.

3. SMACS air-bearing MATLAB®/SIMULINK® model

3.1. Spin rate controller

This model contains the SIMULINK® implementation of the magnetic spin control algorithm, magnetic sensor, actuators and environment and air-bearing table dynamics that is expected to be verified. SIMULINK® and Hardware-In-the-Loop simulations will be done with the fixed Earth's magnetic field. Depending on the spin rate of the air-bearing platform, the magnetometer will measure also magnetic field data at different positions with respect to the environmental magnetic field. It has to be as homogeneous as possible at the temporary location of the air-bearing table. In the presented SMACS model for Air-bearing, magnetic toque rods are utilized to generate magnetic dipole moments in order to control the spin rate using angular momentum of the air-bearing.

The major disturbance torque in air-bearing is due to the misalignment of the adjustable center of mass with the fixed center of rotation. These two points must be co-located in order to remove torque on the system owing to gravity. Even the smallest misalignment causes gravity to torque the platform. Consequently, putting magnetic spin axis control to the test would be arduous

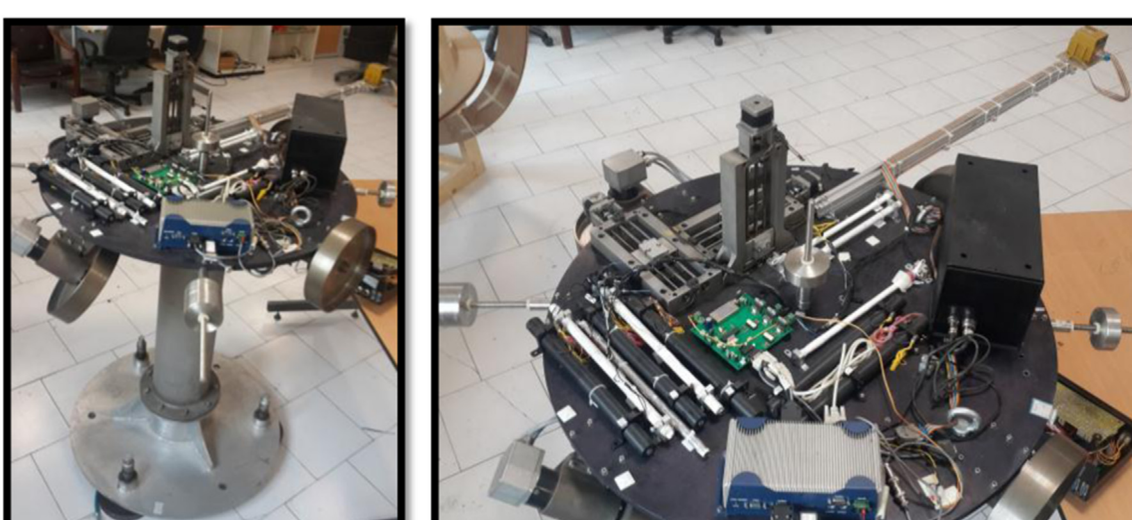

Fig. 1. Configuration of the air-bearing simulator.