Development and Experimentation of a CubeSat Magnetic Attitude Control System Testbed

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Guglielmo Cervettini, Hyeongjun Park*, *Member, IEEE*, Dae Young Lee, *Member, IEEE*, Stefano Pastorelli, and Marcello Romano, *Senior Member, IEEE*

***Abstract*—For CubeSats requiring high pointing accuracy and slewing agility, ground-based hardware-in-the-loop simulations are strongly demanded to test and validate spacecraft subsystems and guidance, navigation, and control algorithms. In this paper, a magnetic attitude control system (MACS) testbed for a CubeSat is developed utilizing a spherical air bearing and a Helmholtz cage. The design, development, and verification procedure of MACS is presented together with different test scenarios. To generate enough torque with the magnetorquer system in the dynamic testbed, the Helmholtz coil system of the testbed has driven to provide an augmented magnetic field. As an example of experimentation, the B-dot control algorithm was implemented to dissipate the angular momentum of the dynamic MACS testbed. The experimental results were compared with those of the numerical simulations.**

***Index Terms*—Magnetic Control, CubeSat, Attitude Control, Hardware-in-the-loop Simulations, Spacecraft.**

I. Introduction

CubeSats are receiving a lot of attention from governmental, commercial, and academic research communities due to their low cost and easy accessibility to space. A technological trend transfer can be observed from passive to active attitude determination and control system (ADCS) approaches [2], [4], [8], [10] as applications of miniaturized satellites expanded. These small satellites are mainly intended for operating in low Earth orbit (LEO). Thus, they must deal with large attitude disturbances, such as aerodynamic drag torque, gravity gradient torque, and magnetic residual torque. These disturbances limit the capabilities of CubeSats to achieve attitude stabilization and control.

Ground-based attitude control testbeds that enable testing and validating guidance, navigation, and control (GN&C) software algorithms and hardware subsystems are strongly demanded [9], in particular, for CubeSats requiring high pointing accuracy and slewing agility. The attitude maneuvers have been successfully completed many times in orbit; however, their performance has usually suffered a slow improvement due to the lack of ground testing. Thus, ground-based attitude control testing is important to validate GN&C software and has recently received significant attention. Specifically, ground testing of a magnetic attitude control system (MACS) is challenging since the Earth magnetic field on the ground is affected by many disturbances, and these disturbances often have an order of magnitude similar to the main control torque. Furthermore, magnetic actuators can only provide a relatively weak torque, and it can hardly overcome the disturbance torques that typically affect ground testbeds, e.g., primarily gravitational torque due to offset between the center of mass and the geometric center of rotation, as well as mechanical friction torques.

In the past, details of the design, realization, and testing of systems for magnetic field simulations have been studied in [5], [14], [15]. In [15], mainly the field intensity and uniformity generated with the Helmholtz cage were focused with the closed-loop control of the magnetic coils' current. Several research groups have developed CubeSat attitude control testbeds including a MACS to validate ADCS of CubeSats in hardware-in-the-loop simulations (HILS) [6], [7], [12], [16], [18]. However, existing research has focused on uni-axial attitude control tests by suspending a CubeSat simulator in a Helmholtz coil system [16] or have implemented simulations utilizing measurement data from magnetometers, a CubeSat on-board computer, and a Helmholtz cage recreating the magnetic environment along the orbit without creating dynamic motions with an air-bearing testbed [6], [7], [18].

While the existing studies have focused mainly on constructive aspects of magnetic attitude control testbeds, implementation of simulations with measured data from magnetometers, or simple uni-axial attitude control tests, we propose a testing method for three-axis attitude control utilizing a Helmholtz cage. In this paper, for the first time to the best knowledge of the authors, a dynamic MACS ground testbed for a CubeSat is constructed and it has tested the three-axis detumbling of a CubeSat using HILS with an augmented magnetic field. The MACS testbed utilizes a hemispherical air bearing to create dynamic motions while minimizing mechanical friction. The design and developing procedure is presented to perform ground testing regarding the main attitude control maneuvers that involve magnetic actuators on CubeSats. To generate enough torque with the magnetorquer system, the Helmholtz coil system of the testbed has driven to provide an augmented magnetic field. This provides the capability to test and validate control algorithms utilizing magnetorquers in the dynamic testbed. As an example test, the B-dot control algorithm was used to detumble the rotating CubeSat testbed with different test scenarios.

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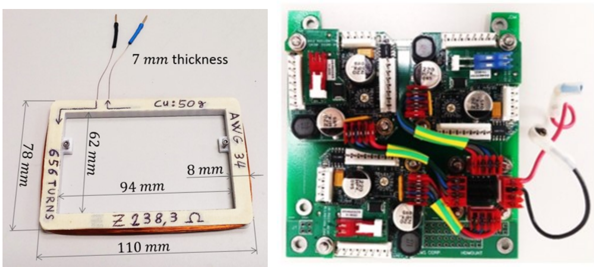


(a) z-axis magnetorquer (b) Magnetorquer driver board

Fig. 1. One of the three magnetorquer and its driver board.

II. Development of a Dynamic MACS Testbed

A. Magnetic Attitude Control System Design

Magnetic attitude actuator has an advantage of constructive simplicity, and it is cheaper and easier to build in-house than other actuators such as reaction wheels and control moment gyroscopes. However, it provides relatively small torque than other actuators because it is strongly depending on the local magnetic field. A magnetorquer is one of the representative magnetic attitude actuator, and consist of coils of copper wire around either a torque rod with core ferromagnetic material or an air-coil magnetorquer with empty core.

In this research, three air-coil magnetorquers are developed for rotational motion control around in the three axes. The customized magnetorquers have the 3D-printed frame as shown in Figure 1. AWG34 copper wire is used for the air-coil magnetorquers. It is a single thread and insulated with enamel. The magnetorquer can generate maximum magnetic dipole moment of $0.248\ Am^2$ with $50\ mA$ current. The design parameters of the customized magnetorquer are summarized in Table I.

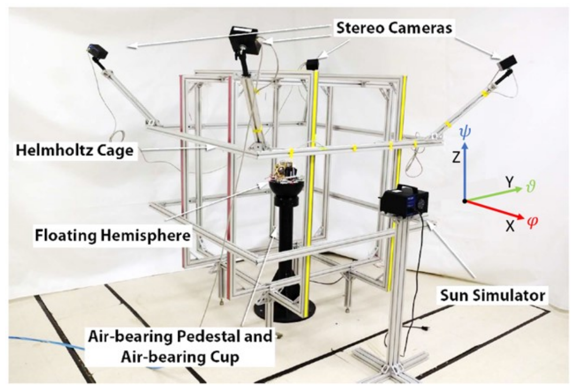
The magnetorquers are driven by three EZHR17EN stepper motor drivers from All-Motions™. The drivers enable current control on an inductive load. The current control is performed through a $40\ kHz$ Pulse Width Modulation (PWM) application of the command voltage to the load, acting on the duty cycle of the command. The assembly of the driver board can provide a maximum $1\ A$ current at $12\ V$. Figure 1 shows the developed magnetorquer system and the EZHR17EN driver board.

B. Integration with CubeTAS

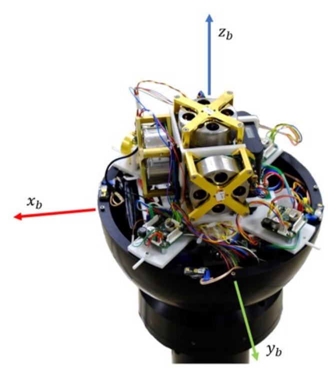
The newly developed MACS is integrated with the CubeSat Three-Axis Simulator (CubeTAS) at the Naval Postgraduate School [3] as shown in Figure 2 to complete a dynamic CubeSat MACS testbed to enable testing detumbling, maneuvering, and momentum unloading using magnetorquers. CubeTAS consists of a hollow floating hemispherical structure containing ADCS components, including three flight-grade reaction wheels, an inertial measurement unit (IMU), a single-board computer (SBC), a battery for a three-axis stabilized spacecraft, and a Helmholtz cage. The hemispherical structure floats over an air bearing so that it enables quasi-frictionless rotational motion with three degrees of freedom (DoF). CubeTAS has the similar size, volume, and mass of a standard 2U CubeSat with actuators and sensors. The system architecture of the floating hemisphere and all the interconnections are represented in Figure 3. The TS-7200 SBC has a $200\ MHz$ ARM9 processor and a PC-104 form factor, and it receives data from the sensors, computes input

TABLE I
Magnetorquer parameters

Parameter	Value
3D printed frame	$110\ mm \times 78\ mm \times 8\ mm$
Average winding area	$74.88 \times 10^{-4}\ m^2$
Copper wire diameter	$0.16\ mm$
Resistance	$238.3\ \Omega$
Maximum magnetic dipole moment	$0.248\ Am^2$ @ $50\ mA$
Mass	$50\ g$



(a) CubeSat Three-Axis Simulator (CubeTAS)



(b) Floating hemisphere of CubeTAS

Fig. 2. (a) CubeTAS [3] and (b) floating hemisphere of CubeTAS.

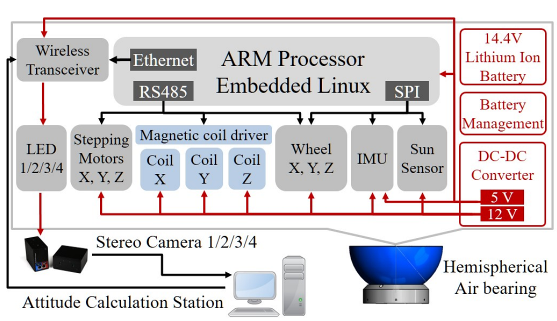
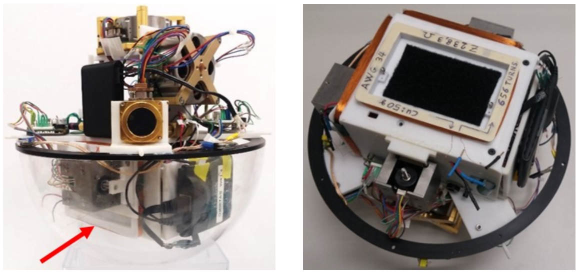


Fig. 3. Hardware architecture of the CubeTAS and MACS.



(a) y-axis magnetorquer (b) z-axis magnetorquer

Fig. 4. Magnetorquer integration with the floating unit of the CubeTAS.

commands, and transmits the commands to the actuators. The SBC supports RS-485, Ethernet, and SPI. The IMU features a triaxial digital accelerometer with an 18 g dynamic range, a triaxial digital gyroscope with 300 deg/s dynamic range, and a triaxial digital magnetometer with a 2.5 Gauss dynamic range in a single micro-electromechanical system package. The three reaction wheels from Sinclair Interplanetary achieves three-axis attitude stabilization and tracking. The power section consists of a lithium battery of 2470 mAh with 14.4 V, a battery management module, and a DC-to-DC converter. The power management module has an 18 V input to the power system. The DC-to-DC converter provides power to all the hardware by converting the power from the power management module to 12 V, 5 V, and 3.3 V.

The dynamic CubeSat MACS testbed was completed by integrating the MACS with CubeTAS. Three pairs of testing pins for the magnetorquers were added to the floating unit. Figure 4 shows the pairs of testing pins (blue color) and the integration of the magnetorquers with the floating unit. Software was developed to allow the SBC to interface with the magnetorquer drivers. In particular, an S-Function that runs on the SBC with the MATLAB/Simulink-based ADCS interfaces with the magnetorquer drivers.

C. Detumbling Control

The spacecraft three-axis simulator's rotational kinematics, to describe orientation, can be expressed using the quaternion vector $\mathbf{q}$ as $\dot{\mathbf{q}} = R(\mathbf{q})\omega$ where $\mathbf{q} = \left[q_1, q_2, q_3, q_4\right]^T$ satisfies the condition $\mathbf{q}^T\mathbf{q} = 1$, and $R(\mathbf{q})$ is given by

$$R(\mathbf{q}) = \frac{1}{2}\begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix} \tag{1}$$

The dynamics of the rotational motion of the spacecraft's angular velocity can be described using Euler's equations,

$$J\dot{\omega} + \omega^{\times}J\omega = M \tag{2}$$

where ω denotes the body angular velocity vector with respect to the body principal axes, M represents the acting torques and J is the body's moment of inertia matrix and estimated as

$$J = \begin{bmatrix} 0.00254 & 6.4117\cdot10^{-5} & -5.6449\cdot10^{-4} \\ 6.4117\cdot10^{-5} & 0.00254 & -4.3863\cdot10^{-4} \\ -5.6449\cdot10^{-4} & -4.3863\cdot10^{-4} & 0.0228 \end{bmatrix} [kgm^2]$$

Detumbling control of CubeSats is important to implement accurate attitude estimation algorithms such as extended Kalman filters. The accurate estimation can be achieved in a detumbled situation to reduce the possibility of sensor malfunctioning. The B-dot control algorithm [13], [17] has been successfully implemented in many CubeSat projects [1] and in a hybrid attitude determination and control algorithm [9], [11]. The B-dot control algorithm is simple and robust against sensor bias. It is given by

$$m_i = -k_b\dot{B}_i, \quad i = x,\ y,\ z, \tag{3}$$

where m_i is the i-th component of the magnetic dipole, $k_b = 1\times10^6$ is a positive constant gain, and $\dot{B}_i$ is the i-th axis component of the time derivative of the geomagnetic field. The B-dot controller was designed in the MATLAB/Simulink™ environment, and implemented for detumbling control.

The designed magnetorquers can provide a very low torque ($\approx 10^{-6}\ Nm$), and can hardly overcome the disturbance torques that distinguish ground testbeds from real orbit experimentation. These disturbances are mainly the gravitational torques due to an imperfect mass balancing of the floating unit. The magnetic torque generated by the noise overlapped to geomagnetic field acts on the floating unit of the testbed together with all the mechanical friction and the air drag. To overcome the issues associated with the disturbances and small torque generation, the available magnetic torque was artificially increased by augmenting magnetic field using the Helmholtz coil system that can generate up to ±2 Gauss in each axis.

III. Test Scenarios and Experimental Results

In this section, we introduce the test scenarios used to validate the MACS, followed by the discussion of the obtained experimental results. The following two scenarios were designed to investigate the dynamic MACS testbed's capability and effectiveness in ground testing.

1) Scenario 1: Detumbling control in the yaw by using the B-dot control.
2) Scenario 2: B-dot control to detumble the floating unit in the three-dimensional motion (roll-pitch-yaw).

A. One-Axis Detumbling Control

In Scenario 1, we tested detumbling control of the magnetorquers only around the yaw axis. To create a reproducible initial condition for the yaw-only rotational motion, the z-axis reaction wheel was used. During the first 4.5 sec of the test, the reaction wheel starts accelerating to reach a constant angular rate, and consequently produces torque. This provides initial angular velocity to emulate tumbling motions of a CubeSat in space. After 4.5 sec, the reaction wheel rotates with a constant angular rate, and the B-dot controller using the magnetorquer system starts to detumble the CubeSat simulator. In this scenario, the augmented magnetic field $\vec{B}$ and the initial constant angular rate $\vec{\omega}_{\text{init}}$ of the CubeTAS floating hemisphere were set to

$$\vec{B} = [-1.670 \quad 0 \quad -0.341\ ]^T \quad [G], \tag{4}$$

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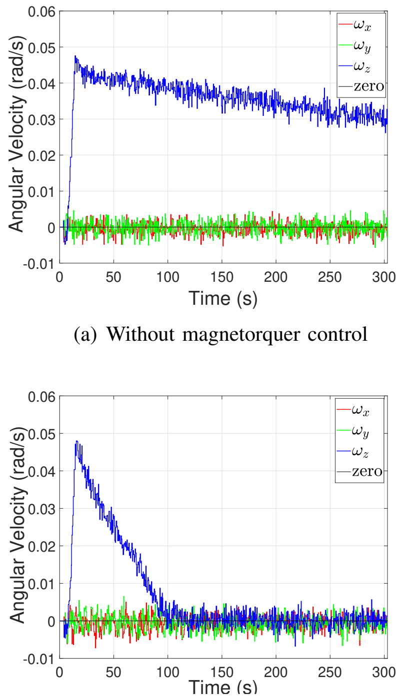


(a) Without magnetorquer control

(b) With magnetorquer control

Fig. 5. Scenario 1: Experimental results with and without the magnetorquer detumbling control in the yaw rotational motion.

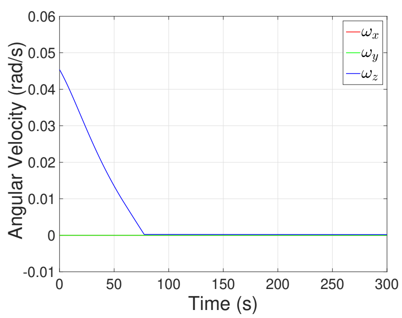
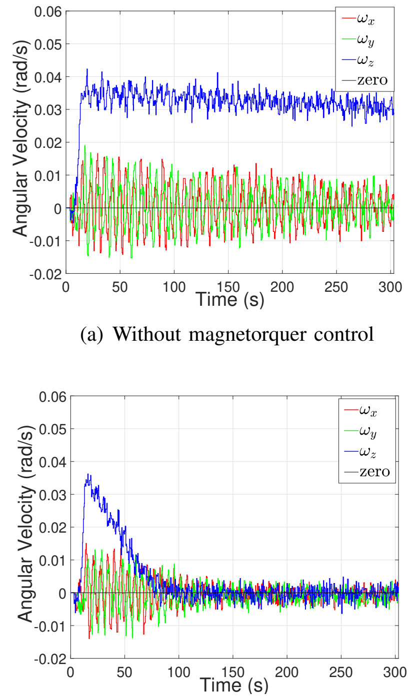


Fig. 6. Scenario 1: Simulation result.

$$\vec{\omega}_{\text{init}} = [\ 0 \quad 0 \quad 0.046\ ]^T \quad [rad/s]. \tag{5}$$

Here, the magnitude of the augmented magnetic field is 1.705 Gauss. It was increased from $\vec{B} = [-0.545 \quad -0.07 \quad -0.297\ ]^T\ G$. Therefore, we consider the 2.73 times larger magnitude of the Earth's magnetic field, and this is approximately three to six times larger magnitude than the value in LEO. The resulting magnitude of the maximum torque generated by the magnetorquers can be $6.5 \times 10^{-5}\ Nm$.

As shown in Figure 5(b), the B-dot controller detumbles the simulator within 81 sec, whereas the floating unit keeps rotating in the z-axis without magnetorquer control as shown in Figure 5(a). Figure 6 shows the simulation results by using the magnetorquer detumbling control in the yaw rotational motion. The elapsed time to stabilize the floating unit in the experiment is 81 sec while the simulation takes 77 sec to stop the spacecraft simulator. The difference is mainly attributed to unmodeled disturbances.



(a) Without magnetorquer control

(b) With magnetorquer control

Fig. 7. Experimental test results with and without the magnetorquer control in the three-axis detumbling control.

B. Three-Axis Detumbling Control

To investigate the performance of the magnetorquer detumbling control for three-axis tumbling motion, a reproducible roll-pitch-yaw tumbling motion was set. During the first 4.5 sec of the tests, the three reaction wheels accelerate and produce torques in the x, y, z-axis. After then, the reaction wheels rotate with constant angular rates, and the detumbling controller starts.

Figure 7 shows the roll-pitch-yaw detumbling maneuver using the B-dot controller on the MACS testbed. The initial condition is created by using the reaction wheels to have a specific angular rate of the test body, e.g., $\omega_x = \omega_y = 0.0242$, $\omega_z = 0.0434\ rad/s$, respectively. The B-dot controller detumbles the rotating spacecraft simulator during 156 sec to stabilize it, whereas the floating unit keeps tumbling without the magnetorquer control.

IV. Conclusions

A dynamic CubeSat magnetorquer attitude control system (MACS) testbed has been developed by integrating the MACS with a spherical air-bearing and a Helmholtz cage for ground testing. By using the Helmholtz coil system, the magnetic field has been locally augmented to provide enough torque enabling the floating unit of the air-bearing testbed to overcome the disturbances. The developed testbed provides the important testing capability for magnetic control systems of CubeSats in dynamic three-axis attitude maneuvering. The comparison of the numerical simulations and the experimental results demonstrated that the experimental results are well-correlated with the simulation. The detumbling control using the magnetorquer system was successfully implemented for two scenario cases. The results were compared with the free rotating cases without the magnetorquer control. Further potential research could involve ground testing of advanced attitude estimation and control algorithms for CubeSats using the developed testbed.

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