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A Dynamic, Hardware-in-the-Loop, Three-Axis Simulator of Spacecraft Attitude Maneuvering with Nanosatellite Dimensions

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Abstract

This paper presents the design and development of a nanosatellite-scale spacecraft three-axis simulator ("CubeSat Three-Axis Simulator," or "CubeTAS"), the purpose of which is to enable experimental testing of Attitude Determination and Control Systems (ADCS) and methods for nanosatellites. The CubeTAS test-bed consists of a hollow hemispherical structure containing typical ADCS components of a three-axis stabilized spacecraft, including the following items: three flight-grade reaction wheels, a sun sensor, an inertial measurement unit, three custom-made magneto-torquer coils, an on-board computer, and a battery. The hemispherical structure and its content float over an air-bearing cup; this enables quasi-frictionless rotation in three degrees of freedom over a large angular displacement.

A custom-made automatic balancing system enables micron-level-accurate coincidence of the center of mass and the center of rotation of the floating system, allowing the achievement of a quasi-torque-free rotation. An off-board, high-accuracy rotational metrology system and an off-board set of three large Helmholtz coils complete the test-bed.

1. Introduction

Since the CubeSat standard was established in 1999, a large number of nanosatellites (<10 Kg) have been developed and launched worldwide (Depasquale et al., 2010), and with increasing nanosatellite developments, there is a need for ground testing and simulation test-beds. In particular, to test and verify a spacecraft's ADCS, hardware-in-the-loop, three-axis simulators are greatly needed. This paper introduces

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an air-bearing, three-axis spacecraft simulator developed for nanosatellites and CubeSats. The end goal of the developed test-bed is to enable verification/validation of attitude determination, control, and guidance software algorithms, as well as testing and validation/verification of hardware subsystems and systems, in particular, for spacecraft requiring high-accuracy pointing and slewing agility.

Spacecraft three-axis simulators have been developed since the 1960s, mostly for large spacecraft (Yang and Cao, 2006; Schwartz, 2004; Jung and Tsiotras, 2003; Nasirian et al., 2006; Schwartz et al., 2003; Romano and Agrawal, 2003). The newly developed CubeSat Three-Axis Simulator (CubeTAS) introduced in this paper is, to the best knowledge of the authors, the first complete three-axis simulator designed and developed for spacecraft of nanosatellite and CubeSat dimensions. A preliminary design architecture of the CubeTAS has been presented in work conducted by Woo et al. (2011). This paper presents the final system design, and shows experimentally the capability of this system to replicate the nanosatellite rotational dynamics.

The CubeTAS test-bed consists of a hollow hemispherical structure containing typical ADCS components of a three-axis stabilized spacecraft, including the following items: three flight-grade reaction wheels, a sun sensor, an Inertial Measurement Unit (IMU), three custom made magneto-torquer coils, a single-board computer (SBC), and a battery. The hemispherical structure and its content float over an air-bearing cup; this enables quasi-frictionless rotational motion in three degrees of freedom (unlimited on yaw and ± 50 deg on pitch and roll). A custom-made automatic balancing system, which includes three masses shifting (driven by linear motors) along three orthogonal directions, enables achievement of micron-level accuracy of coincidence of the center of mass (CM) and the center of rotation (CR) of the floating system, enabling quasi-torque-free rotation. A high-accuracy rotational metrology system, a set of three large Helmholtz coils, and a sun light simulator complete the test-bed.

The current paper is organized as follows: Section 2 introduces the system architecture and the hardware components of the CubeTAS. Section 3 introduces the software architecture and the software development process required to perform an experiment. In Section 4, the results of a sample three-axis stabilization experiment are shown, and Section 5 presents the conclusions.

2. Cubesat Three-Axis Simulator: Hardware Components

2.1. System Design Concept

The CubeTAS system has been designed with two primary goals: 1) to enable high fidelity simulation of the rotational dynamics of a spacecraft in three degrees-of-freedom; and 2) to allow for a simple and rapid experimental testing of spacecraft attitude determination and control algorithms, and hardware subsystems/systems for research and education.

The hardware design took into account size, volume and mass restrictions of nanosatellite. In fact, the system employs actuators and sensors designed for nanosatellites. All of the subsystems are mounted inside the floating hemisphere. Table 1 lists the main parameters of the simulator.

The system configuration allows the user to perform testing of a wide range of attitude determination and control techniques. For example, attitude determination algorithms that use sun sensor and magnetometer readings can be evaluated, since the system is able to simulate the orbital magnetic field and the sun position by means of an Helmholtz cage, and a sun simulator (quartz light), respectively. Guidance and feedback control techniques designed for standard nanosatellite actuators, such as reaction wheels and magnetic torquers, can take advantage of the quasi-torque-free rotational motion simulated by means of the spherical air-bearing.

The software development process allows rapidly designing and experimentally evaluating spacecraft attitude determination, and controlling algorithms. The algorithms are developed using Matlab® and Simulink® (MATLAB, 2007), then compiled and uploaded onto the CubeTAS computer.

Table 1. CubeTAS Main Parameters

Parameters	**Value**
Total Floating Mass	4.3 Kg
Hemisphere Floating Mass	840 g
Attitude Determination Accuracy	.1 deg
Angular Excursion	
Pitch Roll Yaw	±50 deg ±50 deg Unlimited
Inertia Matrix	
I	$\begin{bmatrix} 0.02539 & 6.41167\cdot10^{-5} & -5.64494\cdot10^{-4} \\ 6.41167\cdot10^{-5} & 0.02454 & -4.38634\cdot10^{-4} \\ -5.64494\cdot10^{-4} & -4.38634\cdot10^{-4} & 0.02278 \end{bmatrix}$ Kg-m^2
Endurance Nominal Condition	23 min
Maximum Torque of Each Reaction Wheels	5mNm
Maximum Angular Momentum	50 mNm-s
Maximum Dipole Moment	3.6 Am^2
Maximum Magnetic Field Strength	±2 Gauss

2.2. Overall System Architecture

The CubeSat Three-Axis Simulator (CubeTAS) consists of five main elements (Figure 1): a metrology system composed of four stereo cameras, a Helmholtz Cage, a sun light simulator, an air-bearing pedestal and air-bearing cup, and a floating hemisphere. The metrology system is used to determine the orientation of the floating hemisphere. The Helmholtz cage is used to simulate the Earth's magnetic field as the satellite would experience while on orbit. The sun simulator projects light that is used to simulate the sun light. The air-bearing cup supports the floating hemisphere and provides a quasi-frictionless rotation over three degrees of freedom. The floating hemisphere holds many of the typical subsystems of a nanosatellite. Among the main elements of the CubeTAS, there are wired, wireless, and optical connections. The block diagram representing these connections is shown in Figure 2.

2.3. Rotational Metrology System

The CubeTAS attitude determination hardware is based on the motion capture system developed by PhaseSpace Inc. The system consists of four stereo-vision cameras, one metrology system server, and one quaternion processing station. The cameras are installed on the Helmholtz cage structure as shown Figure 1, and they are connected to the metrology system server, which is also connected to the quaternion processing station.

The four stereo-vision cameras measure the 3D positions of each LED attached to the floating hemisphere body. The task of the metrology system server is to control the camera and to send the positions of each LED to the quaternion processing station.

The quaternion processing computer transforms the data relative to the positions of the LEDs into orientation information of the floating hemisphere. In particular, the absolute orientation problem can be formulated as follows: given *n* points (i.e. the LEDs) and two Cartesian coordinate systems, *a* (fixed with the floating hemisphere) and *b* (fixed with the laboratory), find the rotation matrix (or the quaternions) expressing the orientation of *a* with respect to *b*. In particular, it is possible to write *n* of the following equations, one for each point:

$$r_{b,i} = Rr_{a,i} + r_0 \, , \tag{1}$$

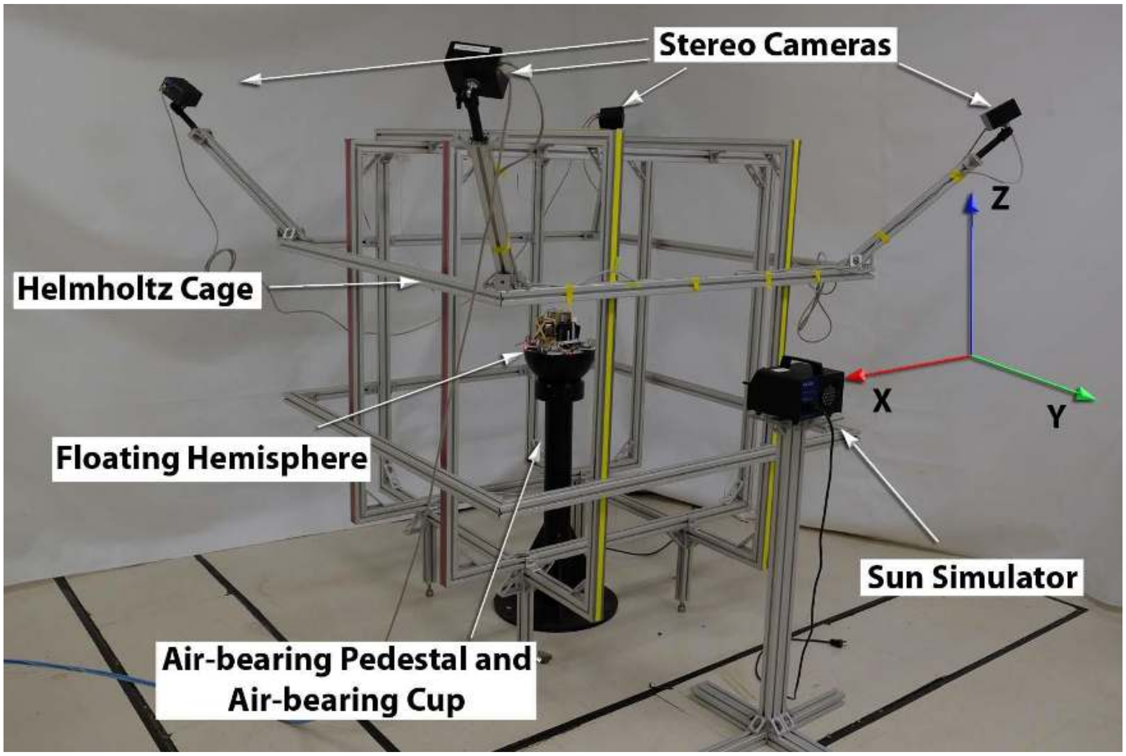


Figure 1. CubeSat Three-Axis Simulator at the Spacecraft Robotics Laboratory of the Naval Postgraduate School.

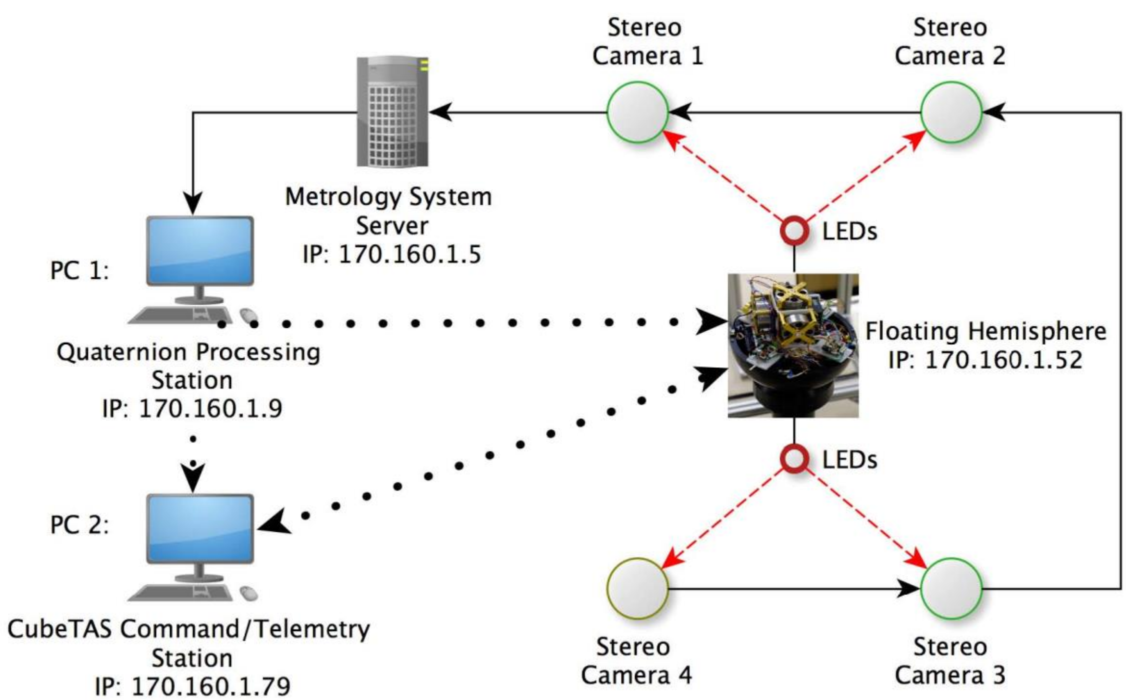


Figure 2. Block diagram of the CubeTAS communication flow. Solid lines are wired connections, dotted lines are wireless connections, and dashed lines are optical connections.

where $r_{a,i}$ and $r_{b,i}$ are the column matrix of position components of point i in the a and b coordinate systems respectively, R is the rotation matrix from a to b and r_0 is the translation offset between the two coordinate systems which can be considered $r_0 = [0, 0, 0]^T$ because the floating hemisphere is fixed in the laboratory coordinate system. Notably, $r_{a,i}$ is time-invariant and measured during a static-test or known by the geometry of the system, while $r_{a,i}$ is time-varying while the floating hemisphere is rotating and is measured by the metrology system.

There are different iterative methods available to solve the absolute orientation problem described by Eqn. (1). A close form solution in the form of unit quaternion is described in Horn (1987) and followed here.

The unit quaternion derived from this solution has ambiguity, caused by the fact that q and $-q$ correspond to the same rotation. Therefore, there are always two ways to rotate from one quaternion to its consecutive, i.e. from q_1 to q_2. On a 4D-unit sphere, the shortest path connecting two consecutive quaternions can be chosen by ensuring that the rotation between them is less than π. In particular, this can be achieved by discarding one of the two quaternions for which the dot product is negative. It is therefore possible to ensure that there are no discontinuities in the successive quaternions. This method has been implemented in the software developed to solve the absolute orientation problem of the floating hemisphere in the quaternion processing station.

To facilitate the visualization of the floating hemisphere's attitude, a Graphical User Interface (GUI) has been developed. The GUI program is a Real-Time 3D visualization of the floating hemisphere's orientation, and allows WiFi data transmission to the floating hemisphere and to the CubeTAS control station.

The GUI has been designed to function as a "Viewer," and does not affect the simulation. The software program can also record the simulation data into a file. The information relative to the floating hemisphere orientation can be sent in the form of Euler angles, quaternion, or simulated sensor output. Because of the high accuracy of the metrology system, the data relative to the attitude can be manipulated to simulate sensors of equal or lower accuracy. For example, by adding noise into the quaternion information, it is possible to simulate sensors with lower accuracy, and the ability to change the streaming frequency can be implemented to simulate sensors with lower update rate, such as star tracker or image sensors.

The software has been developed in C/C++ language using the open source version of the OpenGL Utility Toolkit (GLUT). A screenshot of the program is shown in Figure 3. The GUI program streams each quaternion component in the form of byte array by using user datagram protocol. Each quaternion component is represented in double-precision floating-point format, and is wireless transmitted.

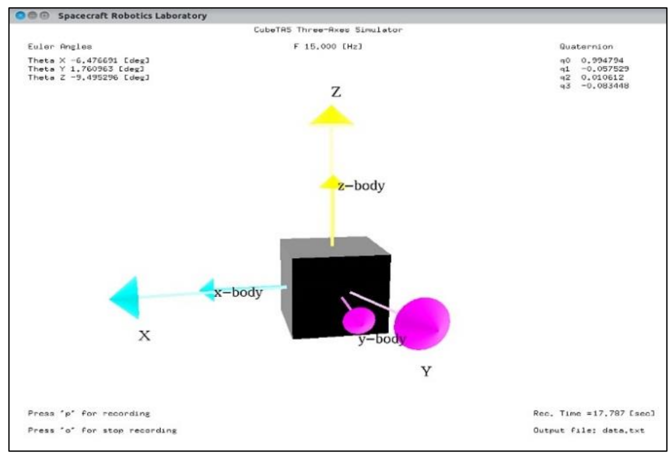


Figure 3. Screenshot of the floating spacecraft simulator orientation in the 3D viewer.

2.4. Hemlholtz Cage System

To experimentally verify attitude determination and control techniques that need magnetic field measurements, the CubeTAS system is equipped with a Helmholtz cage, the design for which is shown with dimensions in Figure 4. The Helmholtz cage is used to generate the magnetic field that the spacecraft would encounter while in orbit. The cage structure is installed around the air-bearing structure, as shown in Figure 1. Each pair of coils structurally supports the others, and in order to minimize the residual magnetic field, the cage was made of aluminum. The Helmholtz cage is able to generate an approximatively uniform magnetic field in a cube of $0.327 m^3$ with a maximum strength of ±2 Gauss. The Helmholtz cage structure holds ≈ 80 winding of 1.291 mm diameter of copper wire per coil.

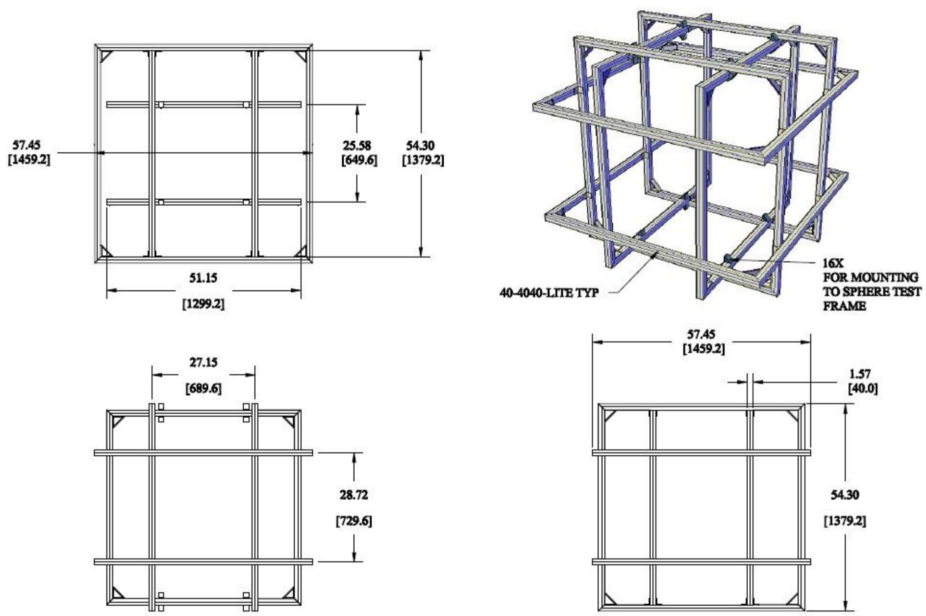


Figure 4. Helmholtz cage design (measurements are in inches [millimeters]).

The choice of using square coils with regard to the circular coils was made for two reasons: 1) square coils allow a simpler fabrication; and 2) as shown in Misakian (2000), the use of square coils generates a larger homogeneous magnetic field w.r.t. circular coil of similar size.

A computer model that propagates the simulated orbit of the spacecraft controls the magnetic field generated by the coils. A controller receives the orbital position and computes the required magnetic field based on the IGRF model (Finlay, 2010). The block diagram of the control system of the Helmholtz cage is shown in Figure 5. The Helmholtz cage control station is equipped with a three-axis digital to analog converter (D/A). Each D/A channel is connected to a power amplifier that provides current to the coils based on the analog input received by the D/A. To compensate for the uncertainties in the coils model, a feedback control is implemented inside the Simulink® model. In fact, the Honeywell magnetometer HMR2300, which has a

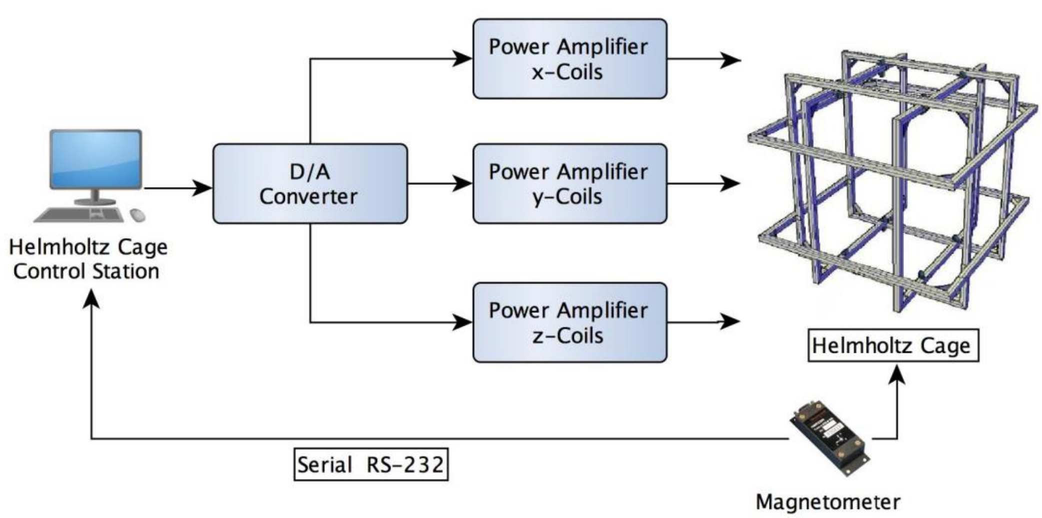


Figure 5. Block diagram of the Helmholtz cage control system.

resolution of 67 μGauss, is placed inside the Helmholtz cage, and provides a constant feedback. The magnetometer is connected to the Helmholtz cage control station through a RS-232 connection.

2.5. Air-Bearing Apparatus

In the interest of minimizing friction, thereby simulating a reduced gravity condition, the floating hemisphere floats over the spherical air-bearing cup. The system has been custom designed, and the production has been outsourced to the company Nelson Air Corp. The operating pressure of the air-bearing is 60 psi, and it has a surface accuracy of 5 μm. Figures 6 and 7 show the air-bearing system design and the hemisphere load analysis, respectively.

Figure 6. Aluminum hemisphere with air-bearing by Nelson Air Corp.

The hemisphere structure was designed to operate under a load of max 40 Kg. This force is applied on the center node along the vertical axis toward the direction of the floating hemisphere. The central node is connected to the outer hemispherical structure by using four anchors. The result of the Finite Elements Methods (FEM) is shown in Figure 7; the hemisphere structural thickness is 1 mm with a mass of 840 g. The material used in the construction of both the floating hemisphere and the air-bearing cup is the aluminum alloy 6061 hard anodize. The hemisphere and the air-bearing were polished together to obtain high surface smoothness and therefore, minimum friction.

2.6. Hemisphere System

The floating hemisphere is the core element of the CubeTAS; its function is to provide three rotational degrees of freedom to simulate the spacecraft rotational dynamics. The floating hemisphere internal structure of the system was built using a 3D printer. The mechanical design goal for the floating hemisphere was to minimize the offset between the center of mass and the center of rotation by taking into account the capabilities of the balancing system. The 3D design was realized on a Siemens PLM Software NX Computer-Aided Design (CAD). The CAD software has the capability of calculating the mass, center of mass, volume, and inertia properties of the system. Therefore, it was possible to use this information to place all the hardware in such a way that the distance between the center of mass of the hemisphere system and the center of rotation was minimized.

Once the design constrains were achieved, the CAD model was transformed in StereoLithography format (STL). The 3D printer for manufacturing uses the STL file.

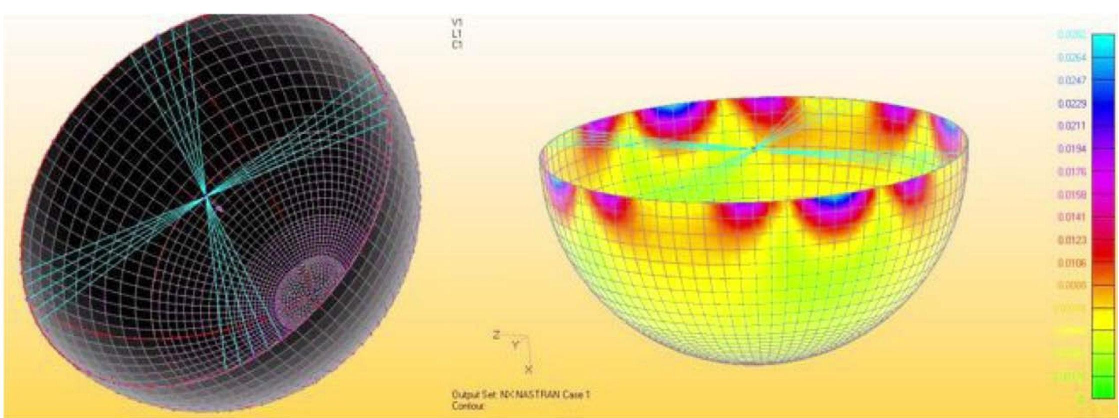
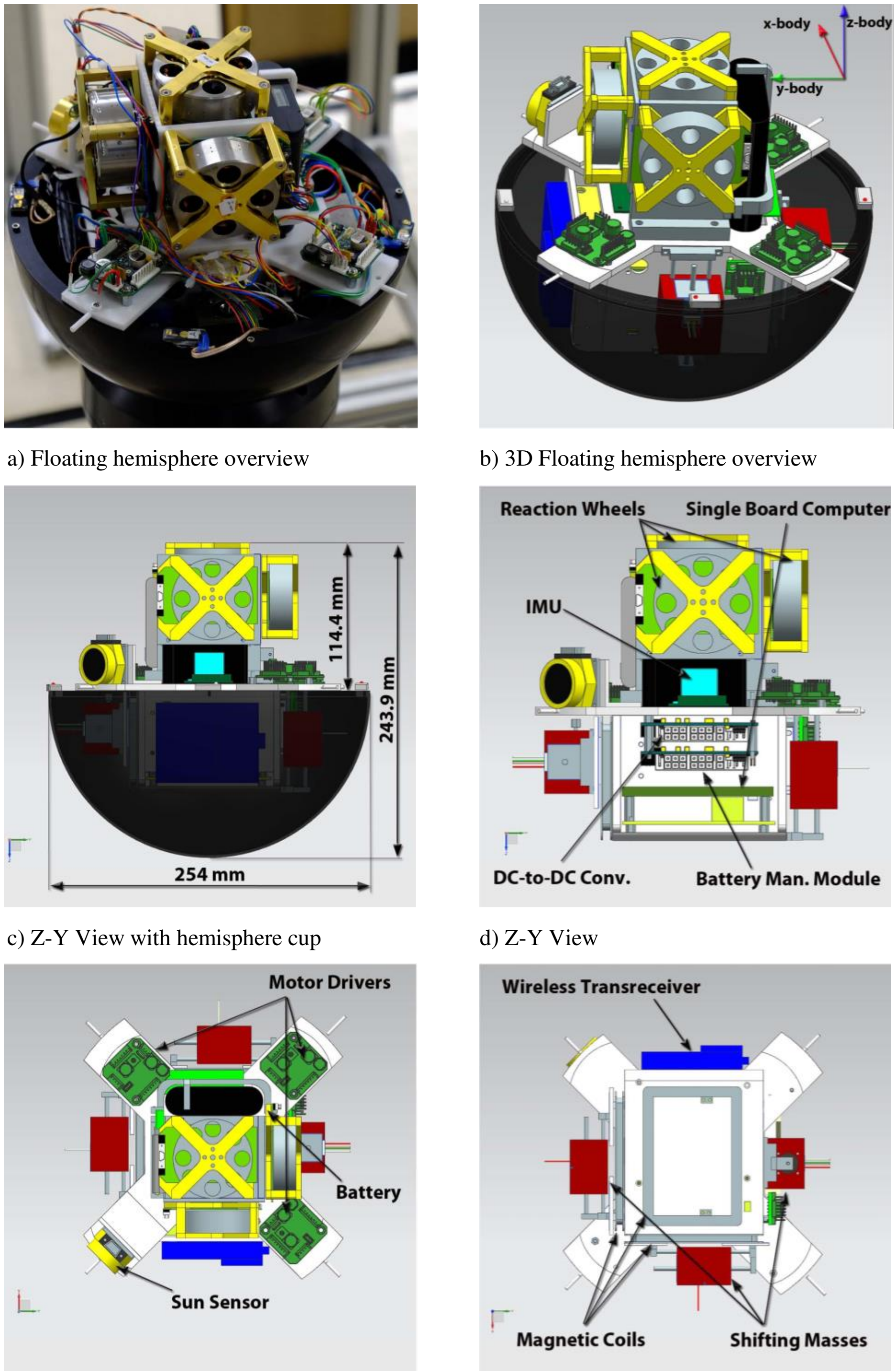


Figure 7. Floating hemisphere finite elements analysis.

The actual design and hardware placement can be seen in Figure 8. The top part of the floating hemisphere structure was designed primarily to hold the reaction wheels' package and battery. Below the reaction wheels package it is possible to identify: IMU, sun sensor, and motor drivers. The lower part of the struc-



a) Floating hemisphere overview

b) 3D Floating hemisphere overview

c) Z-Y View with hemisphere cup

d) Z-Y View

e) Top View

f) Bottom View

Figure 8. Floating spacecraft simulator core overview and components placement.

ture was designed as a box shape. Inside of the lower part are placed: the single-board computer, the magnetic coil driver, and the power management unit. On the outside structure of the bottom part, the shifting masses are attached, as well as the magnetic coils and the wireless transceiver. The list of the floating hemisphere components is reported in Table 2.

The system architecture of the floating hemisphere is represented in Figure 9, where all of the interconnections are also shown. The single-board computer is

Table 2. List of Components of the Floating Hemisphere

Component	Model	Manufacturer
Single-board Computer	TS-7200-32-16F	Technologic Systems
Battery Man. Module	BB-04FR	OceanServer Technology Inc.
Battery	ND2054	Inspired Energy LLC
DC-to-DC Converter	DC-123SR	OceanServer Technology Inc.
Wireless Transceiver	DWL-G730AP	D-Link
LEDs Driver & LEDs	PhaseSpace	PhaseSpace Inc.
Spherical Hemisphere	Custom Made	Nelson Air Corp.
IMU	ADIS16400	Analog Devices
Digital Sun Sensor	SS-411	Sinclair Interplanetary
Reaction Wheels	RW-0.060-28	Sinclair Interplanetary
Magnetic Coil Drivers	EZ17	AllMotion
Magnetic Coils	Custom Made	Spacecraft Robotics Laboratory
Motor Drivers	EZHR17EN	AllMotion
Motors	Non-Captive Series 21000	Haydon Kerk Motion Solutions, Inc

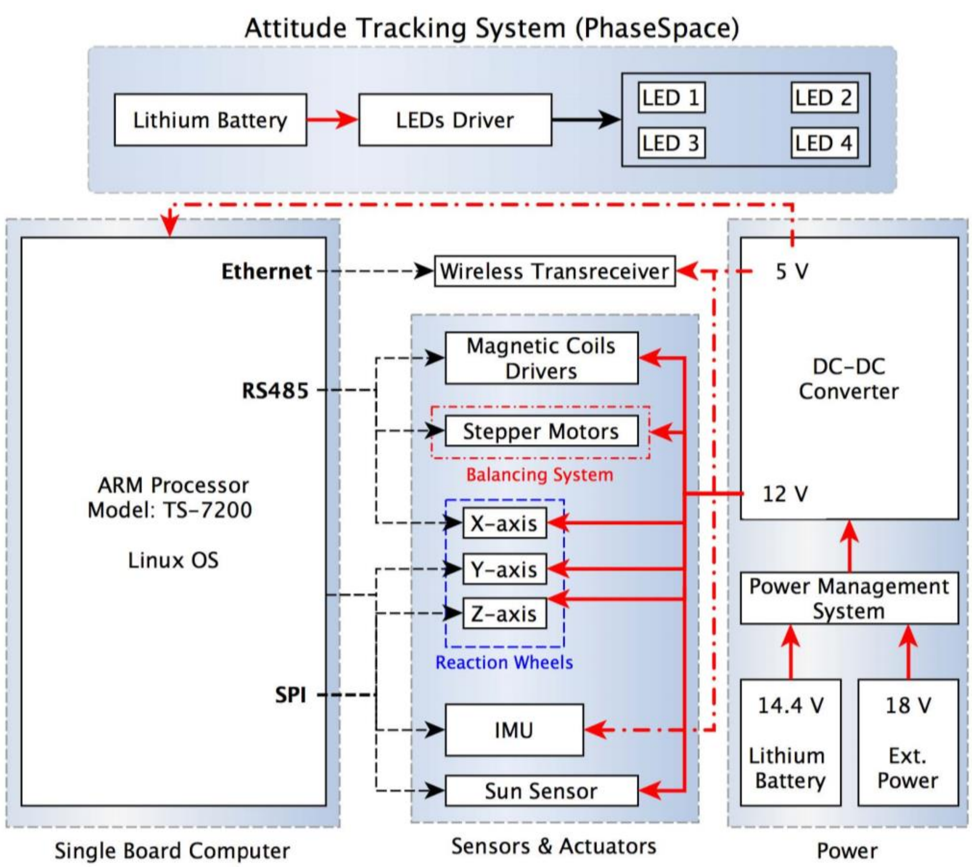


Figure 9. System architecture. Bold or dashed-dotted lines represent power lines; dashed lines represent data lines.

a TS-7200 from Technologic Systems, which has a 200 MHz ARM9 processor and PC-104 form factor. It supports RS485, ethernet, and SPI, and is interfaced with the wireless transceiver, to send and receive data to/from the external systems. The single-board computer was chosen because it supports all hardware communication protocols, and has a low power consumption.

The floating hemisphere is equipped with two sensors: one IMU, and one sun sensor. Both are connected to the single-board computer through SPI. The sun sensor from Sinclair Interplanetary is used to identify the direction of the simulated sun. This sensor provides ±70 deg field-of-view with ±0.1 deg resolution, and was selected because of its flight heritage. The IMU from Analog Devices features a triaxial digital gyroscope with ±300 deg /s dynamic range, a triaxial digital accelerometer with ±18g dynamic range and a triaxial digital magnetometer with ±2.5 Gauss dynamic range in a single microelectromechanical system package.

The floating hemisphere's actuators are: three magnetic coils, three reaction wheels, and three shifting masses. The three custom-made magnetic coils are orthogonally mounted along the body axes, and are driven by three magnetic coil drivers. Each coil driver is connected to the single board computer through RS485. The coils are made by 500 turns of 0.164 mm diameter of copper wires each. The three reaction wheels from Sinclair Interplanetary are used, in combination with the magnetic actuators, to achieve three-axis attitude stabilization. Two of the reaction wheels are connected to the single board computer through SPI, and one is connected via RS485.

The balancing system is composed of three orthogonal shifting masses moved by three stepper linear motors as seen in Figure 10. The stepper motors are surrounded by a brass case, to increase the mass, and therefore the offset compensation capability. Each shifting element has a mass of 243 g. In the mass balancing design, one of the main challenges was to collocate the balancing masses in the space between the lower structure outer walls and the inner wall of the floating hemisphere. In particular, considerable effort was taken to maximize the internal space of the floating hemisphere reserved for components placement, while ensuring the mass balancing translational capabilities.

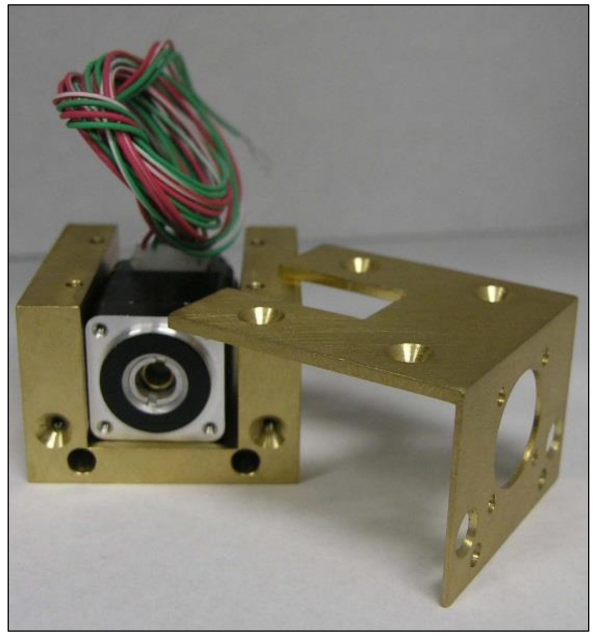


Figure 10. Shifting mass assembly.

The balance masses are about 7% of the whole system weight, which produces the capability to compensate a maximum of 2.1 mm offset between the center-of-mass and center-of-rotation. Each of the stepper motors is controlled by a motor driver, which is connected to the single-board computer via RS485.

The power section includes a lithium battery, battery management module, and the DC-to-DC converter. The battery has a capacity of 2470mAh and produces an output of 14.4V. The power management module also has an 18V input that can be used to power the system and recharge the battery. The DC-to-DC converter converts the power from the power management module to 12V, 5V, and 3.3V, and provides power to all the hardware.

Four LEDs are positioned in a fixed fashion on the floating hemisphere. The LED driver controls the LED lighting. The LED driver makes each of the LEDs blink at a specific frequency and intensity so that they can be uniquely identify by the four stereo vision cameras. Both LEDs and LEDs drivers are fixed on the floating hemisphere, but they have independent software, hardware, and power source with respect to the rest of the system.

3. Cubesat Three-Axis Simulator System: Software Components

3.1. Overall Software Architecture

The CubeTAS software development procedure has been designed to allow simple and rapid GNC algorithm design and implementation. Consequently, the only requirement for a user to develop and test a generic algorithm is a basic knowledge of Matlab® and Simulink®. The software development procedure is shown in Figure 11. The software code is developed on the CubeTAS control station using Simulink®. The communication between the Simulink® model and the experimental hardware is possible by embedding C code into the model using S-functions. The Simulink® model is then transformed into the source code using Realtime Workshop. Since the CubeTAS control station and the floating hemisphere's SBC have different CPU models (ARM and Intel), the GNU ARM cross-compiler is used to create the executable for the ARM processor. The floating hemisphere's SBC runs a minimized linux version wherein the RTAI patch kernel has been provided by Technologic System. Finally, the executable is wirelessly uploaded into the SBC for execution.

3.2. Automatic Balancing Algorithm

To experimentally validate attitude determination and control techniques, a frictionless environment must be simulated. The major disturbance torque affecting air-bearing-based spacecraft simulators is due to the offset distance between the spacecraft simulator center of mass and the spherical air-bearing center of rotation (Smith, 1964).

Spacecraft simulators can employ a manual or an automatic mass balancing system. CubeTAS implements an automatic mass balancing system that uses three shifting masses to relocate the CM close to the CR. Automatic balancing systems offer great advantages in terms of time with respect to manual balancing one. In fact, even a small system modification requires repeating the balancing procedure, and the manual balancing techniques can require hours to be completed. For this reason, different spacecraft simulators have been equipped with an automatic balancing system (Kim and Agrawal, 2009; Prado et al., 2005; Prado and Bisiacchi, 2000; Hatcher and Young, 1968; Yang and Cao, 2006).

In particular, an automatic mass balancing that uses control moment gyros and balancing masses has been proposed by Kim and Agrawal (2009). This automatic balancing system uses the control moment gyroscope (CMG) to track a particular angular momentum, and the error is used as feedback to determine the balancing masses positions.

For the CubeTAS, only the three shifting masses are used to execute the balancing technique (Chesi et al., 2013). In using only three shifting masses, there are some limitations that must be addressed. In fact, the torque generated by the sliding masses is always perpendicular to the gravity field. To successfully balance the system, a two-step design technique was developed. In the first step, the distance between the CM

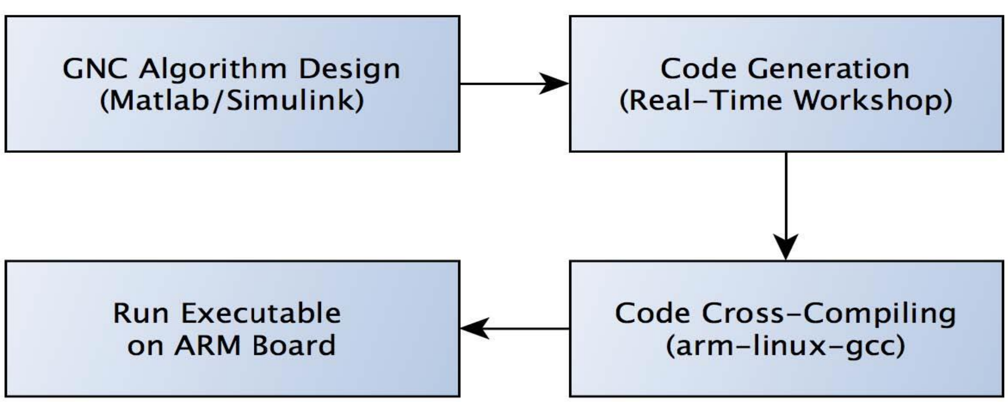


Figure 11. Block diagram of the software development process.

and the CR is compensated in the transversal plane, using nonlinear adaptive feedback control law. Then, in the second step, the imbalance in the last direction is estimated using an Unscented Kalman Filter, and then compensated.

3.3. Attitude Determination and Control System

The block diagram in Figure 12 represents the ADCS block diagram. The signal-processing block is where the output from the metrology system is modified to simulate different types of sensors. The floating hemisphere uses a Kalman filter to determine its attitude based on the measurements provided by the sensors. The control logic computes the required torque that is generated by the reaction wheels or by the magnetic coils, or a combination of both actuators.

4. Sample Experiment: Three-Axis Stabilization

In this sample experiment, the capability of the system to accurately simulate 3DOF spacecraft attitude control is demonstrated. In particular, in this section the result of a three-axis stabilization is reported. The floating hemisphere begins the maneuver starting from a generic orientation and angular velocity. The goal of the maneuver is to achieve a three-axis stabilization, which implies $q \rightarrow q = [0001]^T$ and $\omega \rightarrow \omega_a = a\ [0\ 0\ 0]^T$ *rad/s*, where the subscript *a* represents the reference frame. The 3D stereo camera system provides the high accuracy attitude information and the reference frame for zero attitude condition. To perform the maneuver, a quaternion feedback control has been implemented. The control law used in this experiment is described in Wie (2008), and can be written as

$$u = -K_p q_e - K_d \omega, \quad (2)$$

where $K_p = 0.01$ and $K_d = 0.05$, and $q_e = [q_1\ q_2\ q_3]^T$ is the column matrix with elements equal to the imaginary part of q.

The initial values of attitude and angular velocity with regard to the laboratory coordinate systems were $q = [-0.0029\ 0.1011 - 0.2869\ 0.9526]$ and $\omega = [0.0646 - 0.0480 - 0.1021]$ *rad/s*, respectively. The experimental results are shown in Figures 13 and 14. Figure 13 reports the quaternion components during the maneuver. The maneuver requires about 120 s to converge to the reference attitude. Figure 13b shows the behavior of the spacecraft's angular velocity during the maneuver, which converges to the reference angular velocity in about 120 s.

Figure 14 shows the torque generated and the angular velocities of the reaction wheels during the maneuver. Before performing the maneuver, the reaction wheels' angular velocity was set to $\omega_{rw} = [232\ 232\ 287]$ *rad/s*. The telemetry relative to the torque generated and the reaction wheels' angular velocities in Figure 14a and b are directly provided by the reaction wheels' Hall-effect sensor. After an initial oscillation, the torque components tend to zero as the maneuver is accomplished; consequently, the speed of the reaction wheels becomes a constant.

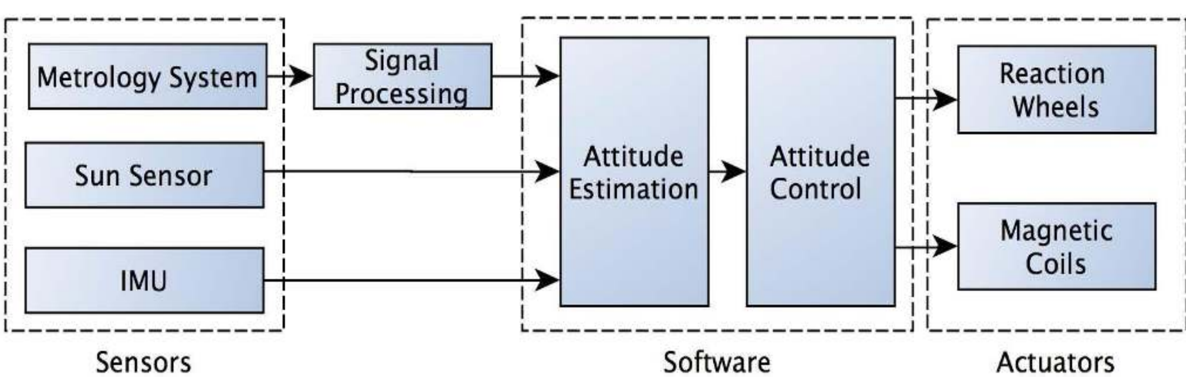


Figure 12. Block diagram of the attitude determination and control system.

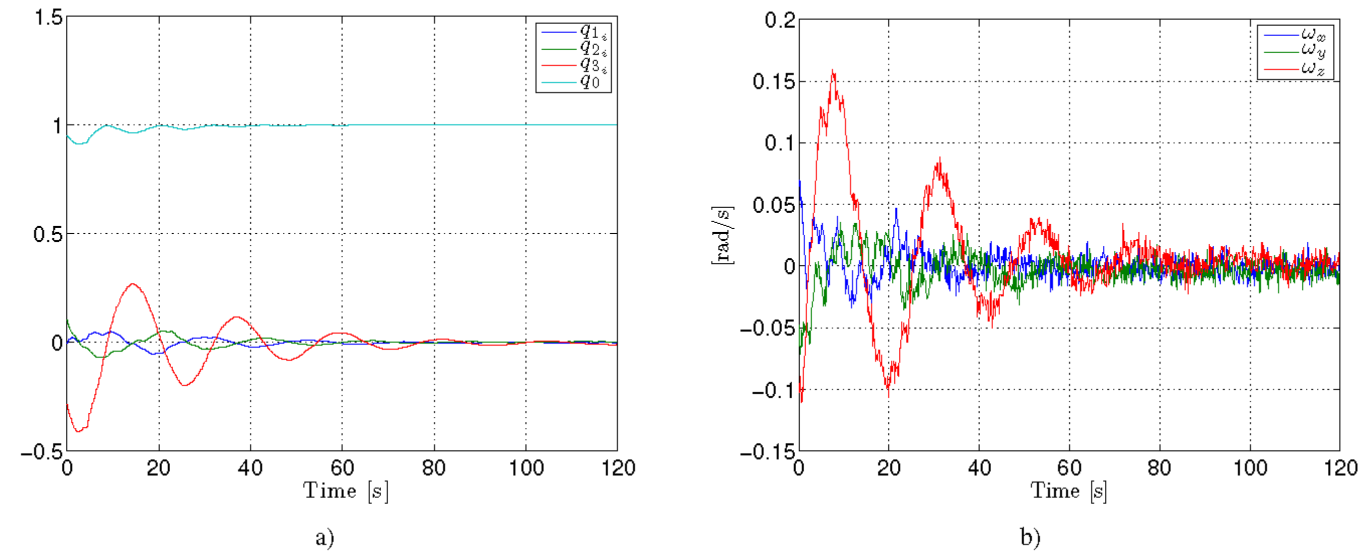


Figure 13. Experimental results: a) quaternion, b) spacecraft angular velocity.

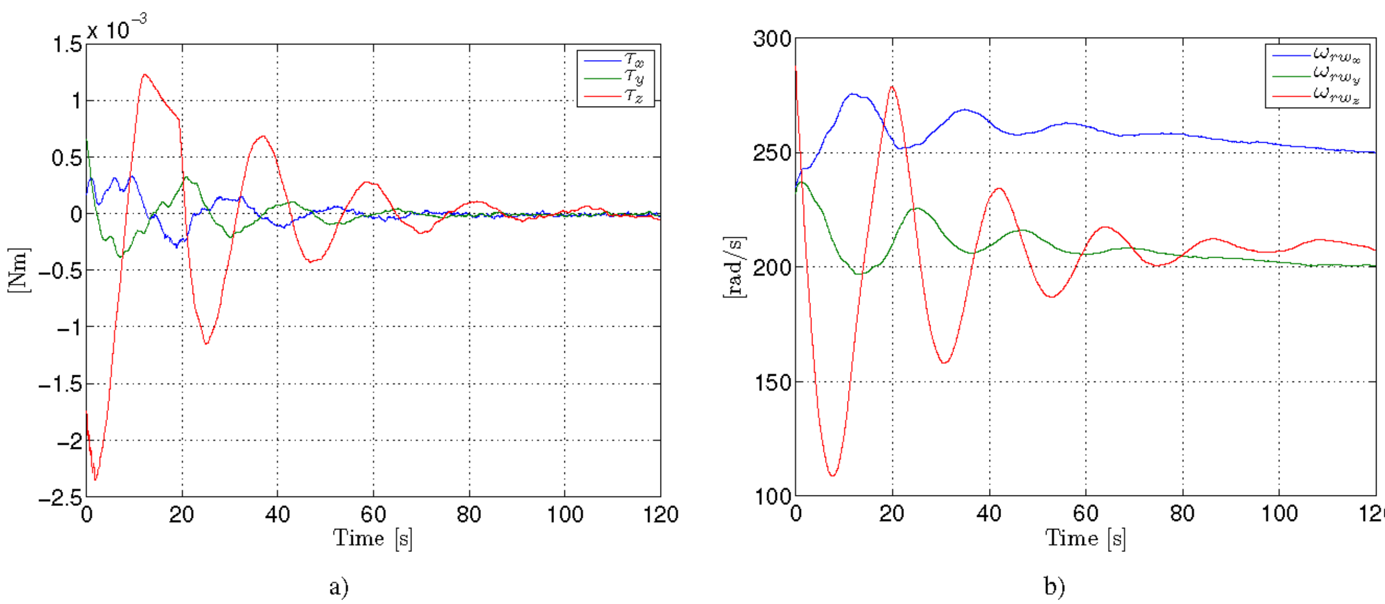


Figure 14. Experimental results: a) torque generated, b) reaction wheels angular velocities.

5. Conclusion

This paper has presented the design and the development of the CubeSat Three-Axis Simulator. This test-bed is designed to simulate the rotational dynamics of nanosatellite-scale spacecraft. In this work, both the hardware and the software have been described in detail. CubeTAS is an effective experimental apparatus for both research and classroom teaching of nanosatellite ADCS, to provide hands-on experience to engineering students. The experimental results presented in this paper demonstrate the capability of the test-bed to successfully simulate the nanosatellite rotational dynamics by performing a three-axis stabilization maneuver. Future work on the CubeTAS will include the validation of attitude control techniques that use magnetic control torques, e.g. detumbling and desaturation.

Acknowledgments

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