SSC17-WK-18

Design and Development of an Unrestricted Satellite Motion Simulator

Eryn Culton, Jeffery T. King, Paige Ward
United States Naval Academy
Aerospace Eng Dept, MS 11B, Annapolis, MD 21402 USA, 410-293-6468
jking@usna.edu

ABSTRACT

The design of most hardware-based spacecraft attitude simulators restricts motion in one or more axes. The problem addressed in this paper is how to design and build a reconfigurable spacecraft model and testbed to simulate the attitude control performance for any satellite. A new satellite attitude dynamics and control simulator and testbed was designed to facilitate unrestricted attitude control algorithm testing which solves the restricted motion problem by using a spherical rotor mounted on an air bearing for a 360°, 3-axis capable testbed. The simulator uses reaction wheels as the momentum exchange device in the satellite since most small satellites with attitude control capabilities use reaction wheels as the preferred means of momentum exchange. Inside the spherical rotor is a reconfigurable inertia model capable of simulating any spacecraft inertia within its design envelope. To establish the design envelope for allowable inertia values, data from over 60 satellites were included. While not all satellites are CubeSats, the emphasis of this paper is the benefit to the smaller CubeSat developer of a low-cost testbed for attitude control algorithm design, validation and demonstration.

BACKGROUND

New attitude control methods and algorithms are regularly being developed. However, they must be tested against specific spacecraft configurations in order to validate new methods and findings.[1,2] The current state of satellite attitude control testbeds is deficient in the ability to completely model three-axis motion. The majority of spherical air-bearing testbeds[3] are either tabletop, dumbbell, or umbrella, which do not provide full 360° rotational motion in all directions. The Unrestricted Satellite Motion Simulator exhibits 360° rotation around all three axes, providing an unrestricted testbed for attitude control algorithms. The inspiration for this simulator came from a demonstration of the EyasSAT (http://eyassat.com/?s=3dof) three degree of freedom CubeSat Air Bearing for classroom demonstration purposes, which was originally designed in cooperation with the United States Air Force Academy.

In addition to exhibiting a larger motion envelope, the Unrestricted Satellite Motion Simulator can be reconfigured with different moments of inertia, imitating an array of spacecraft with minimal or no hardware modifications. Since the Simulator is made to be flexible, it is cost-effective for any spacecraft system. It provides a testbed system to satellite projects allowing new attitude control algorithms to be tested before deployment in space. The Unrestricted Satellite Motion Simulator exhibits the same, real time movement as the actual spacecraft on station in orbit so as to provide a tangible example of attitude control maneuvers.

The Unrestricted Satellite Motion Simulator seeks to provide an attitude control testbed that exhibits 360°, 3-axis capable unrestricted motion in order to most accurately model the freedom of motion in orbit. To accomplish this, a spherical rotor was designed which contains repositionable masses and reaction wheels and a mass balancing system that can accurately place the location of the center of mass of the spherical rotor in whatever mass configuration, resolving the reaction wheel commands to accommodate internal configurations with three, four, or six reaction wheels.

Project Requirements

The following requirements were specified by for the Unrestricted Satellite Motion Simulator:

- Rotate 360° about any axis without restriction.
- Balance the internal masses such that there is no external torque on the system.
- Rotate at a rate up to four degrees per second.
- Communicate wirelessly with external controllers for reaction wheel commanding and performance data retrieval.
- Utilize a spherical rotor that is 15.75 inches in diameter (to match the specified air bearing used).
- Cost effective enough for university and CubeSat project use.

- Provide an accurate representation of on-orbit performance for any satellite being simulated.

SYSTEM DESIGN

Reaction wheels are a popular attitude control system for small spacecraft. They affect a spacecraft's orientation by employing the conservation of momentum and altering the spacecraft's angular velocity. Assuming there are no external torques on the system,[4] the momentum of the entire spacecraft, including the reaction wheels, is constant.

$$h_{sc} + h_{rw} = constant \quad (1)$$

where h_{sc} is the momentum of the spacecraft and h_{rw} is the momentum of the internal reaction wheels. In order to derive a direct relationship between h_{sc} and h_{rw}, the constant in (1) is set to zero to give

$$h_{sc} = -h_{rw} \quad (2)$$

Since momentum is a function of moment of inertia and angular velocity and, assuming a rigid body (i.e. the inertia tensor is constant with respect to time) momentum of a body is proportional to the body's angular velocity.

$$h_{sc} = I_{sc}\omega \quad (3)$$

where I_{SC} is the inertia tensor of the spacecraft in the body frame and ω is the spacecraft rotation rate in the body frame. The momentum produced by each reaction wheel is

$$h_{rw} = I_{rw}\Omega \quad (4)$$

where $I_{rw}$is the inertia of the reaction wheels and Ω is the vector of rotation rates for each of the n reaction wheels. It must be transformed into the body frame using the (3 by n) transformation matrix Z. Substituting (3) and (4) into (2) yields

$$I_{sc}\ \omega = -Z\ I_{rw}\ \Omega \quad (5)$$

The inertia tensor for a given spacecraft is given in the form

$$I = \begin{bmatrix} I_{xx} & -I_{xy} & -I_{xz} \\ -I_{yx} & I_{yy} & -I_{yz} \\ -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \quad (6)$$

However, because most spacecraft are not symmetric, the products of inertia are non-zero. These products of inertia make modeling the spacecraft difficult due to coupling. To simplify this issue, the inertia tensor can be reduced to a principle inertia tensor. In order to complete this reduction, eigenvalues are employed. Solving for the eigenvalues of the spacecraft's moment of inertia

$$|\lambda\ [I] - I_{sc}| = 0 \quad (7)$$

where [I] is the identity matrix. The eigenvalues, λ, are the principle inertia values [I_{p1}, I_{p2}, I_{p3}]. The principal inertia tensor becomes:

$$I_p = \begin{bmatrix} I_{p1} & 0 & 0 \\ 0 & I_{p2} & 0 \\ 0 & 0 & I_{p3} \end{bmatrix} \quad (8)$$

Since they are related by a fixed, constant transformation, it can be assumed that the body axis of a satellite is aligned with the principal axes such that the spacecraft inertia tensor is the principal inertia tensor.

Like a spacecraft, the Unrestricted Satellite Motion Simulator uses the same principles to change orientation and simulate the motion of a spacecraft in orbit. Thus, the equation relating its momentum and the momentum of its reaction wheels is equivalent.

$$I_{sim}\ \omega_{sim} = -Z\ I_{rw_{sim}}\ \Omega_{rw_{sim}} \quad (9)$$

Inertia Ratios

One goal for the Unrestricted Satellite Motion Simulator is to produce the exact same angular velocity as the spacecraft and provide a tangible visualization of the movement of a spacecraft in orbit. Thus,

$$\omega_{sc} = \omega_{sim} = \omega \quad (10)$$

The Unrestricted Satellite Motion Simulator is designed to imitate a variety of spacecraft thus its design includes internal movable masses to allow it to change its moment of inertia. However, spacecraft come in different sizes with different total masses, the Simulator is fixed in size and overall mass. Although the inertia matrices can be reduced into their principle axes, the principle inertia tensors of both the spacecraft and the Simulator must be equivalent for the Unrestricted Satellite Motion Simulator to directly simulate the motion of a satellite in orbit. To equate these potentially extremely different objects, the spacecraft's and Simulator's principle inertia tensors are scaled as ratios, regardless of size, shape, or mass discrepancies. The inertia matrix of the spacecraft is first resolved into its principle inertia tensor. Then, the spacecraft's principle inertia tensor is divided by the value of its largest principle inertia, resulting in a matrix of principle inertia ratios where each value is a ratio of the inertia of one axis in relation to the inertia of the largest axis.

$$\frac{I_{sc}}{I_{max\,sc}} = \begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix} = \frac{I_{sim}}{I_{max\,sim}} \tag{11}$$

where I_{max_sc} is the maximum principal moment of inertia. The Principal Inertia Ratios, D, F, and G, are always less than or equal to 1.0. One of the values will equal exactly 1.0 while the others will vary depending on the inertia of the spacecraft being modeled.

Since the principle inertia ratio tensors of the spacecraft and Simulator are equivalent by design, the momentum between the spacecraft and the Simulator can be related as

$$\frac{h_{sc}}{I_{max\,sc}} = \frac{I_{sc}}{I_{max\,sc}}\omega = \begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix} \omega \tag{12}$$

and

$$\frac{h_{sim}}{I_{max\,sim}} = \frac{I_{sim}}{I_{max\,sim}}\omega = \begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix} \omega \tag{13}$$

Given that both the spacecraft and simulator have the same principle inertia ratio tensors, the angular velocities of the spacecraft and the simulator are maintained as equivalent.

Combining (5), (12), and (13), the relationship between the spacecraft reaction wheels and simulator reaction wheels is established as:

$$\Omega_{sc} = \frac{I_{max_{sc}}}{I_{max_{sim}}} \; \frac{I_{rw_{sim}}}{I_{rw_{sc}}} \; \Omega_{sim} \tag{14}$$

The momentum of the spacecraft can be directly related to the momentum of the simulator's reaction wheels by

$$\frac{I_{sc}}{I_{max_{sc}}}\omega = -Z \; \frac{I_{rw_{sim}}}{I_{max_{sim}}} \; \Omega_{sim} \tag{15}$$

or

$$\begin{bmatrix} D & 0 & 0 \\ 0 & F & 0 \\ 0 & 0 & G \end{bmatrix} \omega = -Z \; \frac{I_{rw_{sim}}}{I_{max_{sim}}} \; \Omega_{sim} \tag{16}$$

which allows the simulator to employ any reaction wheel attitude control and commanding algorithm as if it is the spacecraft and the resultant performance (in terms of angular rate achieved on the body) will be directly measured from the simulator.

Mass Balancing

Gravity can impart external torques on the Unrestricted Spacecraft Motion Simulator if its center of gravity is not located at the center of rotation. If the center of gravity is not located at the center of rotation, gravity's pull on the center of gravity will exert a torque on the system as illustrated in Figure 1 and represented in (17).

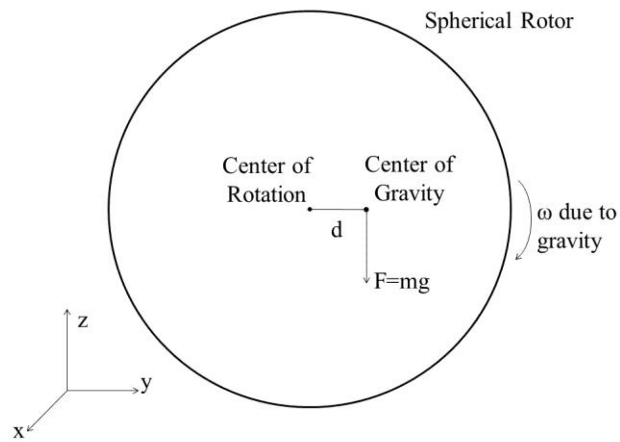

Figure 1. Gravity-based External Torque on Simulator System

$$\tau_g = F \text{ x } d = m\,\alpha \tag{17}$$

where F is the applied force of gravity, d is the distance the center of gravity is removed from the center of rotation, τ_g is torque produced (perpendicular to F and d), m is the mass of the system, and α is the resulting angular acceleration of the system. The angular acceleration causes the system to begin rotating and experiencing an increasing angular velocity until the center of gravity is at its lowest point, where the sphere will eventually come to rest. In order to eliminate the external torques, the locations of the center of gravity and the center of rotation of the sphere must coincide. When d equals zero, the gravitational torque exerted on the system equals zero and no angular acceleration is imparted.

Because the Unrestricted Satellite Motion Simulator is reconfigurable in order to simulate different spacecraft, ensuring its center of gravity is located at the center of rotation before testing is critical to keep system error at a minimum. Ultimately, this becomes a mass balancing problem with an added solution requirement. The masses must not only be balanced about the center of rotation, but they must still create the desired inertia tensor. Mass balancing problems that only require weights to be centered or particularly placed have been solved before; however, the Unrestricted Satellite Motion Simulator's additional inertia constraint transforms the mass balancing issue from something simple, to a more complex and difficult problem. Every time a mass is moved to relocate the center of gravity, the inertia is changed. However, the inertia does not change about that particular axis, it changes about the other two axes that that mass travels around. Since a movement in one axis designed to balance the mass affects the other axes for the inertia tensor, there is complex coupling that occurs for every movement. This is not a problem easily calculated by a human operator and needs an automated algorithm to find a more precise solution than estimating movements and recalculating the inertia tensor manually.

Establishing the Design Envelope

To establish the bounding inertia ratios that the simulator must accommodate, a survey of various satellite inertia tensors was conducted. Published and unpublished data from almost 100 sources (see Appendix A) for more than 60 different spacecraft established the requirements for the simulator.

Absolute inertia values ranged from 0.002 to 93,000 kg-m^2 with mission types including navigation, communication, military, research, university, CubeSat, earth and space science, space telescopes, and interplanetary probes. While not all satellites used reaction wheels, the inertia values were still valuable in establishing the scope of actual inertia ratios. The oldest satellite in the survey is Transit Research and Attitude Control (TRAAC – 1961)[5] with the newest being the James Web Space Telescope (JWST).[6] The sizes of the spacecraft range from a 1U CubeSat like the AAUSat-3[7] to the Hubble Space Telescope (HST).[8]

Figure 2 shows the collected data as ratios. The colors denote which two ratios are being displayed for a given spacecraft, since the third is equal to 1.0. Considering the properties of the inertia tensor, there are physical limits to the values that ratios D, F, and G can take, based on the triangle inequalities:

$$\frac{|D-G|}{F} < 1 \text{ and } \frac{|F-D|}{G} < 1 \text{ and } \frac{|F-G|}{D} < 1 \qquad (18)$$

Values for D, F, and G that violate (18) are not physically realizable and were not considered during the design analysis. The limits of physically realizable inertia values are shown by the black dashed line labeled Triangle Limit in Figure 2.

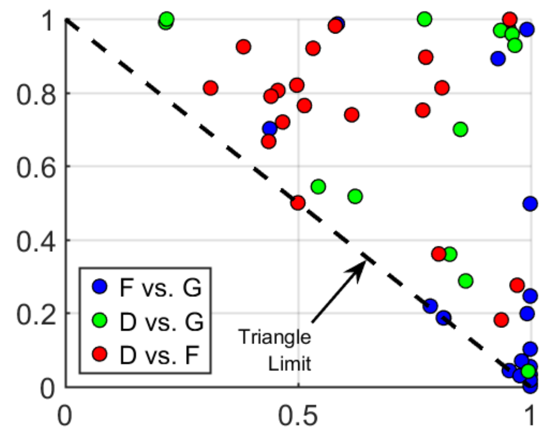

Figure 2: Inertia Ratios from the Survey Data with Triangle Limits Shown.

RESOLUTION INTO PROTOTYPE

A prototype of the Unrestricted Satellite Motion Simulator was initially proposed in 2016 to provide the capabilities described above. To accurately model motion in orbit, the Simulator's external design uses a spherical rotor mounted on a spherical air bearing to provide a frictionless, 360°, 3-axis rotational environment; this environment is necessary in order for the movement of the spherical rotor to act as a free floating object in space with no external forces or restrictions applied to the satellite. The spherical rotor is 15.75 inches in diameter, per the requirements given to fit the specific air bearing.

The air bearing specified for the prototype is a custom manufactured NEWWAY® S36200R200 air bearing (http://www.newwayairbearings.com). Instead of having a small number of orifices for air to support the rotor, the air bearing has a porous carbon surface with millions of orifices purposed to distribute air across the entire surface. This allows for a smooth and uniform pressure profile with which to support the spherical rotor and provide a frictionless surface. Additionally, because the entire block is porous and can deliver air, the air bearing is scratch resistant: even if the surface becomes scratched or scuffed, air will still be delivered out of the scratches and an even air layer will continue to be provided.

The air bearing for the Unrestricted Satellite Motion Simulator was custom designed to hold a 15.75 inch outer diameter spherical rotor. It is capable of supporting a load of several hundred pounds and, as a result, can provide ample support for the Unrestricted Satellite Motion Simulator whose total weight is approximately 25 pounds.

Mounting and Storage Structure

When not in operation, the spherical rotor sits above a hole in its shelf surrounded by a foam bowl to keep it in place and to prevent the clear acrylic shell from scratching (see Figure 3).

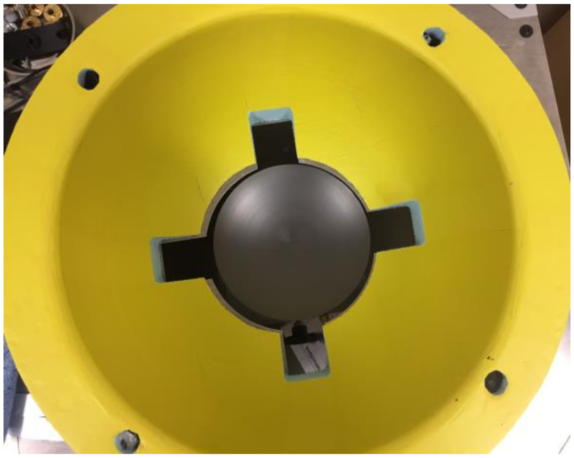

Figure 3. Top View of Empty Foam Bowl with NEWWAY Air Bearing Below

The air bearing sits below the spherical rotor on a moveable platform that can be raised to meet the bottom of the rotor, as shown in Figures 4 and 5. The air bearing is connected to an air compressor with desiccant and oil filters to prevent particulates from clogging the air bearing. The air compressor is portable and is capable of continuous use for 15 minutes.

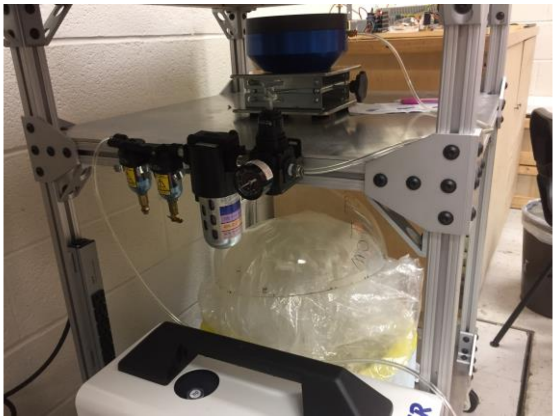

Figure 4. Air Filters and NEWWAY Air Bearing on Adjustable Platform

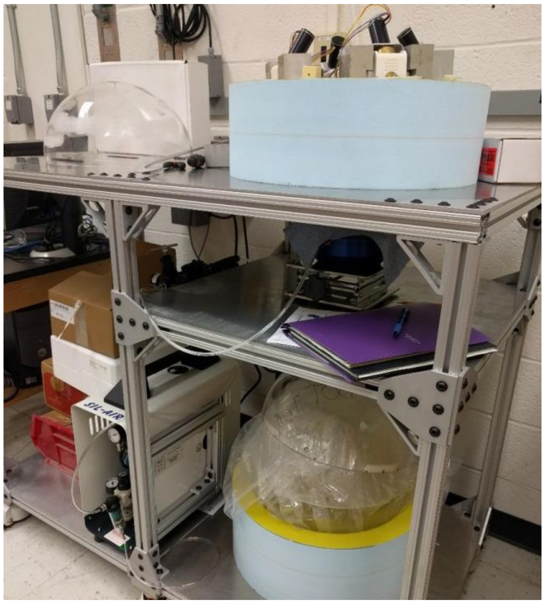

Figure 5. External View of the Unrestricted Satellite Motion Simulator Cart

Internal Design

In order to model multiple spacecraft, the Simulator includes an internal variable mass modeler which represents spacecraft based on its principle inertia ratios. Specifically, the rotor includes six, independently moveable masses located on each of the positive and negative coordinate axes. The Mass is carried on a traveler, which also carries the reaction wheel and associated battery pack (see Figure 6). The travelers were 3D printed on site and designed for a specific reaction wheel configuration. Each mass weighs approximately two kilograms. This value maximizes the inertia changes within the operating envelope of the spherical rotor while also being light enough to ensure an overall slew rate of four degrees/second is maintained by the reaction wheels.

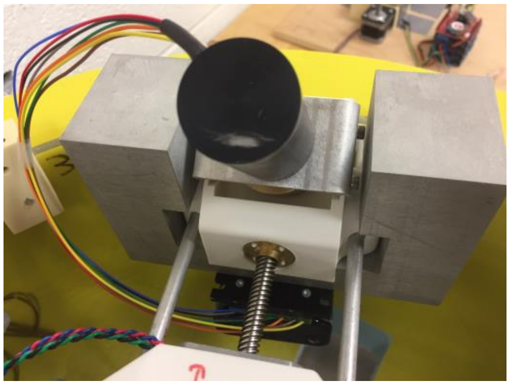

Figure 6. +Y-Axis Mass Traveler with Reaction Wheel Assembly and Attached Mass

Slew rate is calculated from how much torque the reaction wheels produce and the overall mass of the rotor and its internal components. Thus, to ensure a four degree/second slew rate capability, the added masses must not make the total mass of the system exceed a specific weight.

Each mass is controlled by a stepper motor, shown in Figure 7. These stepper motors allow each mass to move independently within the rotor, expanding the range of attainable inertia ratios and increasing the number of satellites the simulator is capable of imitating. The stepper motors are attached to a threaded nut on which the masses are mounted. When the shaft rotates, the masses are moved laterally on the shaft, affecting their position within the rotor.

Figure 7. Stepper Motor with Threaded Shaft and Mounting Nut

Control of the Simulator attitude is achieved with up to six reaction wheels, mounted on the moveable masses. The prototype simulator includes a set of four Faulhaber brushless DC motors with a custom built wheel; one of each on the positive and negative x- and y-axes, oriented in a standard pyramidal configuration as shown in Figure 8 and illustrated in Figures 9-10.

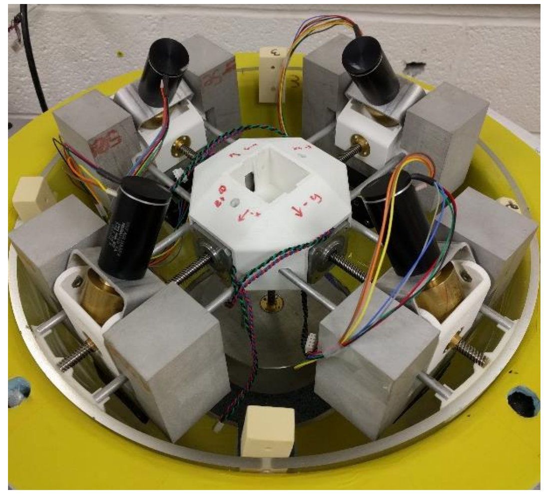

Figure 8. Internal Components of the Unrestricted Satellite Motion Simulator (with Top Hemisphere and +Z-Axis Traveler Removed)

The pyramidal configuration provides redundant three axis control, ultimately allowing the Simulator to experience three dimensional rotation, and is a common configuration for systems with four reaction wheels. In order to represent these four wheels in the body frame, a reaction wheel alignment matrix, Z, is required. The reaction wheel alignment matrix follows a NASA standard four-wheel configuration[9] and is given by

$$Z = \begin{bmatrix} \cos(\eta) & 0 & -\cos(\eta) & 0 \\ 0 & \cos(\eta) & 0 & -\cos(\eta) \\ \sin(\eta) & \sin(\eta) & \sin(\eta) & \sin(\eta) \end{bmatrix} \quad (19)$$

with η=35.26° as the optimal fixed angle for the maximum spherical torque envelope[10] and is shown in Figure 10.

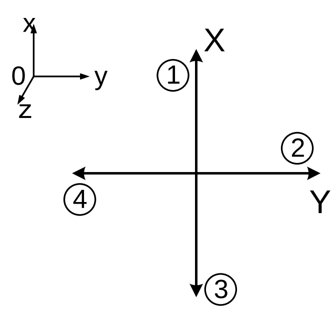

Figure 9: Reaction Wheel Configuration in X-Y Plane.

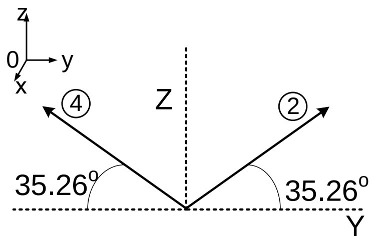

Figure 10: Reaction Wheel Configuration in Y-Z Plane.

The Simulator is controlled wirelessly during normal operations. The prototype includes a system of xBee 2.4 GHz wireless radios, which relay commands in and data out of the sphere, and an Arduino processor which directs the stepper motors. Each reaction wheel has its own controller which communicates via the xBee to the laptop for commanding. The xBee and Arduino controller are located within the +z-axis mass traveler as shown in Figure 11. The +z-axis mass traveler also houses the battery pack for these elements. Located on the center block, an Adafruit 9-DOF inertial measurement unit (IMU) will measure the rotation of the simulator. Externally, there is a laptop computer running algorithms to wirelessly control and monitor the reaction wheels and different data systems. The attitude control algorithm performance data displays on this laptop in real time and is also recorded for later analysis.

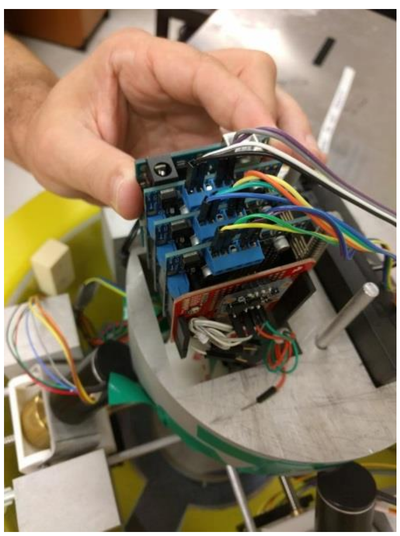

Figure 11. +Z-Axis Mass Traveler with xBees (Blue) and Arduino Controller

Calibration and Testing

Before every test, the Simulator's systems must be balanced and calibrated to ensure accuracy. First, the desired inertia ratio matrix will be entered into the system and the masses will move to the appropriate locations to create the same inertia ratio matrix for the spherical rotor. The system of masses will then be balanced, ensuring the center of gravity is located at the center of rotation. To accomplish this, the rotation rate of the sphere will be measured via the internal IMU while the reaction wheels are at rest to calculate the torque on the spherical rotor due to the displacement between the center of gravity and the center of rotation. The displacement will be calculated from the torque produced; as a result, movement of the masses to relocate the center of gravity will be estimated. The masses will be moved while making sure the new placement of the masses still satisfies the inertia ratio matrix. This process will repeat until the rotational rate induced on the sphere due to the displacement between the center of gravity and center of rotation is insignificant enough to not affect the results of any attitude control algorithm test.

Whenever a new reaction wheel configuration is installed, the reaction wheels must also be calibrated. Once the system is balanced, each reaction wheel must be individually spun up to speed to ensure operation. Next, the system of reaction wheels must be spun such that the sphere rotates about the body frame's x-axis. This should be repeated around the y- and z- axes as well to ensure full 360°, 3 axes rotation is possible and at the rate that is expected.

FUTURE WORK

Ultimately, the mass balancing and calibration should be entirely autonomous. Instead of balancing the masses by manually estimating where to reposition the masses given the calculated displacement between the centers of gravity and rotation, there will be an autonomous algorithm that will continually iterate until the masses are balanced. Having the computer calculate the exact distance the masses should be moved while simultaneously ensuring the desired inertia ratio matrix is achieved will be quicker and more accurate than the manual process.

The first generation spherical rotor was not manufactured precisely enough to ensure a symmetrical, spherical shape. Instead, the sphere bulges around the equator, preventing the rotor from rotating freely about the x- or y-axes. Research into alternate materials, manufacturers, and mold methods is being conducted to solve this issue.

CONCLUSION

Although the Unrestricted Satellite Motion Simulator is only a prototype at the moment, it was designed as a fully functional, accurate, and flexible attitude control algorithm testbed. This testbed is capable of simulating numerous satellites and their reaction control systems. The design envelope was established using actual spacecraft across the spectrum of sizes to ensure universal applicability of the simulator to any future satellite project. Most importantly, this simulator eliminates the biggest restriction of current simulators by providing the capability to test satellite rotation about any axis without restriction. The ability to demonstrate and validate new attitude control methods and algorithms on hardware that accurately represents the satellite system is critically valuable for any program, but especially those programs whose budget or schedule do not allow for expensive testing apparatus.

ACKNOWLEDGMENTS

We gratefully acknowledge the support from Dr. Mark Karpenko at the Naval Postgraduate School in funding and guidance.

The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Government.

REFERENCES

1. J. King and M. Karpenko, "Estimation of Optimal Control Benefits Using the Agilitoid Concept," 25th Annual AAS/AIAA Space Flight Mechanics Meeting, Williamsburg, VA, Jan. 2015.

2. J. T. King, M. Karpenko, and I. M. Ross, "Rapid Collection of Large Areas for Imaging Spacecraft," 25th Annual AAS/AIAA Space Flight Mechanics Meeting, Williamsburg, VA, Jan. 2015.

3. D. M. Meissner, "A Three Degrees of Freedom Test-bed for Nanosatellite and Cubesat Attitude Dynamics, Determination, and Control," Master's thesis, Mech Engr Dept, Naval Postgraduate School, Monterey, CA, Dec 2009.

4. Sidi, Marcel J. *Spacecraft Dynamics & Control*. Edited by Michael Rycroft, Robert Stengel, Cambridge University Press, 1997.

5. G. G. Herzl and W. W. Walker, "Passive Gravity Gradient Libration Dampers," Tech. Rep. SP-8071, NASA, Washington, DC, Feb. 1971.

6. L. Meza, F. Tung, S. Anandakrishnan, V. Spector, and T. Hyde, "Line of Sight Stabilization of James Webb Space Telescope," 27th Annual AAS Guidance and Control Conference, Breckenridge, CO, Feb. 2005.

7. K. Jensen, F. and K. Vinther, "Attitude Determination and Control System for AAUSAT3," Master's thesis, Dept. Electronic Systems, Aalborg University, Aalborg, Germany, June 2010.

8. J. K. Thienel and R. M. Sanner, "Hubble Space Telescope Angular Velocity Estimation During the Robotic Servicing Mission," Journal of Guidance, Control, and Dynamics, Vol. 30, Jan. 2007, pp. 29–34.

9. F. L. Markley and J. L. Crassidis, Fundamentals of Spacecraft Attitude Determination and Control. New York: Springer, 2014.

10. F. L. Markley, R. G. Reynolds, F. X. Liu, and K. L. Lebsock, "Maximum Torque and Momentum Envelopes for Reaction Wheel Arrays," Journal of Guidance, Control, and Dynamics, Vol. 33, Oct. 2010, pp. 1606–1614.

APPENDIX A

The following papers, document, and websites were consulted in building the Inertia Survey data set.

S. Nasir Adeli, “Attitude Control And Deployment Of Nano-Solar Sail Spacecraft,” Ph.D., University of Surrey, 2011.

B. N. Agrawal and R. E. Rasmussen, “Air-bearing-based satellite attitude dynamics simulator for control software research and development,” *Proceedings of SPIE*, vol. 4366, pp. 204–214, 2001.

P. Appel, “Attitude estimation from magnetometer and earth-albedo-corrected coarse sun sensor measurements,” *Acta Astronautica*, vol. 56, no. 1–2, pp. 115–126, Jan. 2005.

J. Auret, “Design of an aerodynamic attitude control system for a CubeSat,” Thesis, Stellenbosch : Stellenbosch University, 2012.

H. Bang, M.-J. Tahk, and H.-D. Choi, “Large angle attitude control of spacecraft with actuator saturation,” *Control Engineering Practice*, vol. 11, no. 9, pp. 989–997, 2003.

G. A. Beals, R. C. Crum, H. J. Dougherty, D. K. Hegel, And J. L. Kelley, “Hubble Space Telescope precision pointing control system,” *Journal of Guidance, Control, and Dynamics*, vol. 11, no. 2, pp. 119–123, 1988.

E. Bergmann and J. Dzielski, “Spacecraft mass property identification with torque-generating control,” *Journal of Guidance, Control, and Dynamics*, vol. 13, no. 1, pp. 99–103, Jan. 1990.

R. Boynton, “Using a spherical air bearing to simulate weightlessness,” *Weight Engineering*, vol. 56, no. 2, pp. 37–47, 1996.

R. Boynton, “Using a spherical air bearing to simulate weightlessness,” *Weight Engineering*, vol. 56, no. 2, pp. 37–47, 1996.

G. Bråthen, "Design of Attitude Control System of a Double CubeSat", Masters, Norwegian University of Science and Technology, 2013.

D. Bruno, "Contingency Mixed Actuator Controller Implementation for the Dawn Asteroid Rendezvous Spacecraft", in AIAA SPACE 2012 Conference and Exposition, 2012.

T. D. V. Bui, K. S. Low, Z. Lau, V. H. P. Pham, and M. S. C. Tissera, “System design and development of VELOX-I nanosatellite,” in *2015 IEEE Aerospace Conference*, 2015, pp. 1–7.

R. Cameron, T. Aldcroft, W. Podgorski and M. Freeman, "Initial Performance of the Attitude Control and Aspect Determination Subsystems on the Chandra Observatory", NASA, 2000.

M. Catalon, "Attitude Control of the Spacecraft TARANIS: Sun Acquisition Robustness", Masters, Royal Institute of Technology, 2012.

Y.-K. Chang, B.-H. Lee, and S.-J. Kim, “Momentum wheel start-up method for HAUSAT-2 ultra-small satellite,” *Aerospace Science and Technology*, vol. 10, no. 2, pp. 168–174, Mar. 2006.

J. R. Chaurais *et al.*, “A high precision attitude determination and control system for the UYS-1 nanosatellite,” in *Aerospace Conference, 2013 IEEE*, 2013, pp. 1–12.

Y.-P. Chen and S.-C. Lo, “Sliding-mode controller design for spacecraft attitude tracking maneuvers,” *IEEE Transactions on Aerospace and Electronic Systems*, vol. 29, no. 4, pp. 1328–1333, Oct. 1993.

V. Chu, A. Wu and P. Chen, "ROCSAT-3 Constellation Mission", in *AIAA/USU SmallSat Conference*, Logan, UT, 2003.

B. Clarke, "Ice, Cloud, and Land Elevation Satellite: Orbital Maintenance and Recovery", 2003. [Online]. Available: http://ccar.colorado.edu/asen5050/projects/projects_2003/clarke/. [Accessed: 30- Jun-2015].

C. Crowell, "Development and Analysis of a Small Satellite Attitude Determination and Control System Testbed", Massachusetts Institute of Technology, Cambridge, MA, 2011.

K. Daly, P. Hattis and K. Cox, "Space Flight Experience with the Shuttle Orbiter Control System", NASA National Aeronautics and Space Administration, Langley, 1983.

W. Dellinger and H. Shapiro, "Attitude Control on Two Wheels and No Gyros - The Past, Present, and Future of the TIMED Spacecraft", in AIAA/AAS Astrodynamics Specialist Conference and Exhibit, Honolulu, Hawaii, 2008.

C. Dennehy, T. Kia and R. Welch, "Attitude determination and control subsystem for the TOPEX satellite", in Guidance, Navigation and Control Conference, 1988.

R. DORUK, "NONLINEAR CONTROLLER DESIGNS FOR A REACTION WHEEL ACTUATED OBSERVATORY SATELLITE", Ph. D., Middle East Technical University, 2008.

A. Friedman, B. Underhill, S. Ferring, C. Lenz, J. Rademacher, and H. Reed, "Arizona State University Satellite 1 (ASUSat1): Low-Cost, Student-Designed Nanosatellite," *Journal of Spacecraft and Rockets*, vol. 39, no. 5, pp. 740–748, Sep. 2002.

K. Fukuda, T. Nakano, Y. Sakamoto, T. Kuwahara, K. Yoshida, and Y. Takahashi, "Attitude control system of micro satellite RISING-2," in *System Integration (SII), 2010 IEEE/SICE International Symposium on*, 2010, pp. 373–378.

J. Gerber, "A 3-axis attitude control system hardware design for a CubeSat", Masters Thesis, Stellenbosch University, 2014.

D. Gerhardt, "Passive Magnetic Attitude Control for CubeSat Spacecraft." [Online]. Available: http://lasp.colorado.edu/home/csswe/files/2012/06/Gerhardt_SSC10_PMAC.pdf. [Accessed: 08-Jul-2015].

A. Ginati, "The TUBSAT-1 Attitude Control and Stabilization System," *AIAA/USU Conference on Small Satellites*, Sep. 1989.

P. Graven, Y. Plan, L. J. Hansen, and S. Harvey, "Implementing Plug-and-Play ADCS to Support Operationally Responsive Space," in *2008 IEEE Aerospace Conference*, 2008, pp. 1–14.

P. Graven, K. Kolcio, Y. Plam, and L. J. Hansen, "Implementation of a Plug-and-Play attitude determination and control system on PnPSat," in *Aerospace conference, 2009 IEEE*, 2009, pp. 1–13.

T. Hao and S. Matunaga, "Analysis and precision attitude control using control moment gyro for rapid multi-target observation," in *2013 6th International Conference on Recent Advances in Space Technologies (RAST)*, 2013, pp. 869–874.

G. G. Herzl and W. W. Walker, "Passive Gravity Gradient Libration Dampers," Tech. Rep. SP-8071, NASA, Washington, DC, Feb. 1971.

N. M. Horri and S. Hodgart, "Attitude stabilization of an underactuated satellite using two wheels," in *2003 IEEE Aerospace Conference, 2003. Proceedings*, 2003, vol. 6, p. 6_2629-6_2635.

S. Hosokawa, Y. Masumoto, S. Takezawa, and K. Haneji, "Damping Control by One-Axis Magnetic Torquer and Gravity Gradient Attitude Stabilization for Small Satellite," *Transactions of the Japan Society for Aeronautical and Space Sciences*, vol. 49, no. 164, pp. 94–100, 2006.

S. Hurley, B. Williams, D. Balke and W. Davids, "Operational Challenges Presented by the Future Orbit of the Chandra X-Ray Observatory", in *SpaceOps 2010 Conference*, NASA Mars, 2010.

R. Iwens, G. Bernier, R. Hofstadter, R. Mayo and H. Nakano, "Design Study for LANDSAT-D Attitude Control System", TRW Defense and Space Systems Group, Redondo Beach, CA, 1977.

Y. W. Jan and J. C. Chiou, "Attitude control system for ROCSAT-3 microsatellite: a conceptual design," *Acta Astronautica*, vol. 56, no. 4, pp. 439–452, Feb. 2005.

K. Jensen F. and K. Vinther, "Attitude Determination and Control System for AAUSAT3," Masters Thesis, Dept Electronic Systems, Aalborg University, Aalborg, Germany, 2010.

C. Johnson, "TACSAT I Nutation Dynamics", in 3rd Communications Satellite Systems Conference, Los Angeles, CA, 1970.

M. Kabganian, M. Nabipour, and F. F. Saberi, "Design and implementation of attitude control algorithm of a satellite on a three-axis gimbal simulator," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 229, no. 1, pp. 72–86, Jan. 2015.

O. Khurshid, P. Janhunen, A. Visala, J. Praks and M. Hallikainen, "Attitude Dynamics Analysis of Aalto-1 Satellite During De-orbit Experiment with Plasma Brake", in 63rd International Astronautical Congress, Naples, Italy, 2012.

B. J. Kim, H. Lee, and S. D. Choi, "Three-axis reaction wheel attitude control system for KITSAT-3 microsatellite," *Space Technology*, vol. 5–6, no. 16, pp. 291–296, 1996.

J. J. Kim and B. N. Agrawal, “Automatic Mass Balancing of Air-Bearing-Based Three-Axis Rotational Spacecraft Simulator,” *Journal of Guidance, Control, and Dynamics*, vol. 32, no. 3, pp. 1005–1017, May 2009.

C. Grantham and P. Kurzhals, "A System for Inertial Experiment pointing and Attitude Control", National Aeronautics and Space Administration, Hampton, VA, 1966.

V. J. Lappas, W. H. Steyn, and C. Underwood, “Design and Testing of a Control Moment Gyroscope Cluster for Small Satellites,” *Journal of Spacecraft and Rockets*, vol. 42, no. 4, pp. 729–739, Jul. 2005.

A. Y. Lee and J. A. Wertz, “In-Flight Estimation of the Cassini Spacecraft’s Inertia Tensor,” *Journal of Spacecraft and Rockets*, vol. 39, no. 1, pp. 153–155, 2002.

C. Lee and A. Lee, "Cassini Reaction Wheel Momentum Bias Optimization Tool", in AIAA Guidance, Navigation, and Control Conference and Exhibit, San Francisco, CA, 2005.

G. Macala, “Design of the reaction wheel attitude control system for the Cassini spacecraft,” *Advances in the Astronautical Sciences*, vol. 112, pp. 303–315, 2002.

M. C. Mahdi *et al.*, “Attitude Determination and Control System design of KufaSat,” *International Journal of Current Engineering and Technology*, vol. 4, no. 4, 2014.

M. Mahdi, A. Hassan and J. Jaafer, "New Deployable Solar Panel Array for 1U NanoSatellites", *ARPN Journal of Engineering and Applied Sciences*, vol. 9, no. 11, pp. 2322-2326, 2014.

Amanda K. Mainzer, et al., “Pointing calibration and reference sensor for the Space Infrared Telescope Facility,” Proc. SPIE 3356, Space Telescopes and Instruments V, 1095-1105, August 28, 1998.

F. L. Markley, F. H. Bauer, J. Deily, and M. D. Femiano, “Attitude control system conceptual design for Geostationary Operational Environmental Satellite spacecraft series,” *Journal of Guidance, Control, and Dynamics*, vol. 18, no. 2, pp. 247–255, Mar. 1995.

T. Marshall, T. Gunderman and F. Mobley, "Reaction Wheel Control of the MSX Satellite", in *Annual Rocky Mountain guidance and Control Conference*, Keystone, CO, 1991, pp. 119-138.

M. I. Martinelli and R. S. Sánchez Peña, “Passive 3 axis attitude control of MSU-1 pico-satellite,” *Acta Astronautica*, vol. 56, no. 5, pp. 507–517, Mar. 2005.

R. McEwen, “Overview of the Miniature Sensor Technology Integration (MSTI) spacecraft attitude control system,” in *Flight Mechanics/Estimation Theory Symposium*, 1994, vol. 1, pp. 281–295.

C. McLean, D. Pagnozzi, and J. Biggs, “Computationally light attitude controls for resource limited nano-spacecraft,” in *62nd International Astronautical Congress 2011*, 2011, p. Paper–IAC.

D. M. Meissner, “A Three Degrees of Freedom Test-bed for Nanosatellite and Cubesat Attitude Dynamics, Determination, and Control,” Master’s thesis, Mech Engr Dept, Naval Postgraduate School, Monterey, CA, Dec 2009.

M. A. Mendoza-Bárcenas, E. Vicente-Vivas, and H. Rodríguez-Cortés, “Mechatronic Design, Dynamic Modeling and Results of a Satellite Flight Simulator for Experimental Validation of Satellite Attitude Determination and Control Schemes in 3-Axis,” *Journal of Applied Research and Technology*, vol. 12, no. 3, 2014.

L. Meza, F. Tung, S. Anandakrishnan, V. Spector, and T. Hyde, “Line of Sight Stabilization of James Webb Space Telescope,” in *27th Annual AAS Guidance and Control Conference*, Breckenridge, CO, 2005, vol. AAS 05-002.

F. F. Mobley, W. E. Radford, and L. R. Kennedy, “MSX Attitude determination and control hardware,” *Johns Hopkins APL Technical Digest*, vol. 17, no. 2, p. 153, 1996.

M. Ovchinnikov, V. Pen’ko, O. Norberg, and S. Barabash, “Attitude control system for the first swedish nanosatellite ‘MUNIN,’” *Acta Astronautica*, vol. 46, no. 2–6, pp. 319–326, Jan. 2000.

M. Y. Ovchinnikov, A. A. Ilyin, N. V. Kupriynova, V. I. Penkov, and A. S. Selivanov, “Attitude dynamics of the first Russian nanosatellite TNS-0,” *Acta Astronautica*, vol. 61, no. 1–6, pp. 277–285, Jun. 2007.

M. Ovchinnikov, V. Penkov, A. Ilyin and S. Selivanov, "Magnetic Attitude Control Systems of NanoSatellite TNS-Series", Russian Academy of Sciences and Russian Research Institute, Moscow, Russia, 2004.

M. A. Peck, L. Miller, A. R. Cavender, M. Gonzalez, and T. Hintz, “An Airbearing-Based Testbed For Momentum Control Systems And Spacecraft Line Of Sight,” *Advances in the Astronautical Sciences*, vol. 114, pp. 427–446, 2003.

M. Quadrino, "Testing the Attitude Determination and Control of a CubeSat with Hardware-in-the-Loop", Masters, Massachusetts Institute of Technology, 2014.

S. Rhee and J. Lee, "On-Orbit Performance of KOMPSAT-2 Attitude and Orbit Control System", in *AIAA/USU SmallSat Conference*, Logan, UT, 2007.

R. F. Richfield, B. K. Walker, and E. V. Bergmann, “Input selection for a second-order mass property estimator,” *Journal of Guidance, Control, and Dynamics*, vol. 11, no. 3, pp. 207–212, May 1988.

G. R. Ricker *et al.*, “Transiting Exoplanet Survey Satellite,” *J. Astron. Telesc. Instrum. Syst*, vol. 1, no. 1, pp. 014003–014003, 2014.

A. Samuel and B. Lechable, "An Overview on Aerospatiale Magnetic Bearing Products for Spacecraft Attitude Control and for Industry", in *Third International Symposium on Magnetic Suspension Technology, Part 1*, National Aeronautics and Space Administration, 1996, pp. 217-226.

A. G. Santo *et al.*, “The MESSENGER mission to Mercury: spacecraft and mission design,” *Planetary and Space Science*, vol. 49, no. 14–15, pp. 1481–1500, Dec. 2001.

J. L. Schwartz and C. D. Hall, “System identification of a spherical air-bearing spacecraft simulator,” *AAS Paper*, vol. 122, 2004.

J. L. Schwartz, M. A. Peck, and C. D. Hall, “Historical review of air-bearing spacecraft simulators,” *Journal of Guidance, Control, and Dynamics*, vol. 26, no. 4, pp. 513–522, 2003.

J. Schwartz, "The Distributed Spacecraft Attitude Control System Simulator: from Design Concept to Decentralized Control", Ph. D., Virginia Polytechnic Institute and State University, 2004.

E. Silani and M. Lovera, “Magnetic spacecraft attitude control: a survey and some new results,” *Control Engineering Practice*, vol. 13, no. 3, pp. 357–371, Mar. 2005.

H. Sira-RamíRez and H. B. Siguerdidjane, “A redundant dynamical sliding mode control scheme for an asymptotic space vehicle stabilization,” *International Journal of Control*, vol. 65, no. 6, pp. 901–912, Dec. 1996.

N. Smith, "Disturbance Rejection for the Ice, Cloud, and Land Elevation Satellite One Hertz Pointing Oscillation", in *AIAA Guidance, Navigation, and Control Conference and Exhibit*, Keystone, CO, 2006.

S. Spremo, M. Lindsay, P. Klupar and A. Swank, "Cost Optimization and Technology Enablement COTSAT-1", in *Small Satellites Systems and Services 4S Symposium*, Madeira, Portugal, 2010.

M. Steckling, U. Renner, and H.-P. Röser, “DLR-TUBSAT, qualification of high precision attitude control in orbit,” *Acta astronautica*, vol. 39, no. 9, pp. 951–960, 1996.

I. T. Stengle, “Mechanics/Estimation Theory Symposium,” in *NASA Conference Publication*, 1988, vol. 301.

W. H. Steyn, “An Attitude Control System for SumbandilaSAT an Earth Observation Satellite,” presented at the ESA Special Publication, 2008, vol. 660, p. 83.

W. Steyn, "In-Orbit AODCS Performance of SUMBANDILASAT an Earth Observation Satellite for South Africa", *in 61st International Astronautical Congress*, Prague, Czech Republic, 2010.

N. Sugimura *et al.*, “Ground test of attitude control system for micro satellite RISING-2,” in *System Integration (SII), 2012 IEEE/SICE International Symposium on*, 2012, pp. 301–306.

S. Tanygin and T. Williams, “Mass Property Estimation Using Coasting Maneuvers,” *Journal of Guidance, Control, and Dynamics*, vol. 20, no. 4, pp. 625–632, Jul. 1997.

J. K. Thienel and R. M. Sanner, “Hubble Space Telescope Angular Velocity Estimation During the Robotic Servicing Mission,” *Journal of Guidance, Control, and Dynamics*, vol. 30, no. 1, pp. 29–34, Jan. 2007.

V. C. Thomas *et al.*, “The Dawn Spacecraft,” *Space Science Reviews*, vol. 163, no. 1–4, pp. 175–249, Dec. 2011.

J. D. Tuthill, “Design and simulation of a nano-satellite attitude determination system,” Masters Thesis, Monterey, California. Naval Postgraduate School, 2009.

Y. M. Urlichich, A. S. Selivanov, and A. A. Stepanov, “Two nanosatellites for space experiments,” in *Digest for Fifth International Symposium of IAA “Small Satellites for Earth Observation”, Berlin, Germany*, 2005, vol. 4.

B. Wang, K. Gong, D. Yang, and J. Li, “Fine attitude control by reaction wheels using variable-structure controller,” *Acta Astronautica*, vol. 52, no. 8, pp. 613–618, Apr. 2003.

R. Waschburger, D. A. Santos, and J. Waldmann, “Magnetotorquer-Only Attitude Control System Robust to Wide Range of Initial Conditions for Low-Cost Spin-Stabilized ITASAT Satellite,” *Preceedings of COBEM*, 2009.

M. W. Werner *et al.*, “The Spitzer Space Telescope Mission,” *ApJS*, vol. 154, no. 1, p. 1, Sep. 2004.

W. R. Wilson, L. L. Jones, and M. A. Peck, “A Multimodule Planar Air Bearing Testbed for CubeSat-Scale Spacecraft,” *Journal of Dynamic Systems, Measurement, and Control*, vol. 135, no. 4, p. 045001, 2013.

C.-H. Won, “Comparative study of various control methods for attitude control of a LEO satellite,” *Aerospace Science and Technology*, vol. 3, no. 5, pp. 323–333, Jul. 1999.

T. Xiang, T. Meng, H. Wang, K. Han, and Z.-H. Jin, “Design and on-orbit performance of the attitude determination and control system for the ZDPS-1A pico-satellite,” *Acta Astronautica*, vol. 77, pp. 182–196, Aug. 2012.

L. Xu, J. Chen, G. Chen, X. Shao, and D. Duan, “The attitude tracking maneuvers of spaceborne spotlight SAR,” in *2010 3rd International Symposium on Systems and Control in Aeronautics and Astronautics (ISSCAA)*, 2010, pp. 29–33.

B. Young, "Design and Specification of an Attitude Control System for the DANDE Mission", Masters, University of Colorado, 2008.

J. Young, "Balancing of a Small Satellite Attitude Control Simulator on an Air Bearing", Utah State University, Logan, UT, 1998.

R. Zeledon and M. Peck, "Attitude Dynamics and Control of a 3U CubeSat with Electrolysis Propulsion", in *AIAA Guidance, Navigation, and Control Conference*, Boston, MA, 2013.

"Tsubame (Demonstration Microsatellite of TITech, Tokyo)", *EO Portal Directory*, 2014. [Online]. Available: https://directory.eoportal.org/web/eoportal /satellite-missions/t/tsubame. [Accessed: 30- Jun- 2015]