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Spherical Air Bearing Attitude Control Simulator for Nanosatellites

Tyler Ustrzycki[1]
York University, Toronto, Ontario, Canada, M3J 1P3

Dr. Regina Lee[2]
York University, Toronto, Ontario, Canada, M3J 1P3

and

Hugh Chesser[3]
York University, Toronto, Ontario, Canada, M3J 1P3

Spherical Air Bearing systems have been used as a testbed for attitude control systems for many decades. With the advancements of nanosatellite technologies as a platform for scientific missions, there is an increased demand for comprehensive, pre-launch testing of nanosatellites. Several spherical air bearing systems have been developed for larger satellite application and add too much parasitic mass to be applicable for nanosatellite applications. This paper focuses on the design and validation of a Spherical Air Bearing Attitude Control Simulator for Nanosatellites. The simulator consists of the physical design of the system, a complete electronics system, and validation of the simulator using low-cost reaction wheels as actuators. The design of the air bearing platform includes a manual balancing system to align the centre of mass with the centre of rotation. The electronics system is intended to measure the attitude of the platform and control the actuator system. Validation is achieved through a controlled slew maneuver of the air bearing platform.

I. Introduction

In recent years, nanosatellites have increasingly been recognized as valuable tools for demonstrating new technologies and scientific endeavours. Their light weight and low cost allow for technological and scientific principles to be demonstrated quickly and effectively. As nanosatellite missions become more involved, more thorough space qualification is also required. Comprehensive testing prior to launch can significantly improve survivability in space.

Spherical air bearing systems are a method of simulating the torque free motion experienced by satellites in orbit. These systems provide freedom along the rotational axes. Spherical air bearing systems use a thin film of air passing between concentric spheres to create a torque-free environment. No spherical system can offer unconstrained motion along all three rotational axes. There are two basic configurations for a spherical air bearing system; tabletop or umbrella system as shown in Figure 1. Both configuration offers a full 360° rotation about the yaw axis and usually between ±90° in the pitch and roll axis[1].

This paper focuses on design and validation of a spherical air bearing attitude control simulator for nanosatellites, in particular CubeSat based spacecrafts. The simulator is a tabletop spherical air bearing system which comprises the air bearing and platform, manual

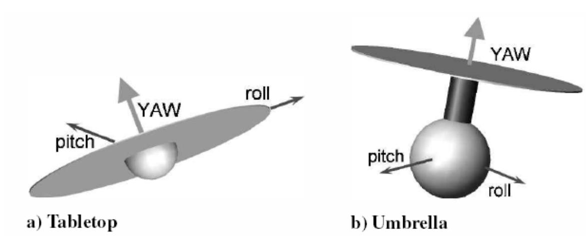

Figure 1. Tabletop (a) and Umbrella (b) Configurations[1]

[1] MSc. Candidate, Earth and Space Science, 4700 Keele St. Toronto, Ontario, M3J 1P3 and AIAA Student Member.
[2] Assistant Professor, School of Engineering, 4700 Keele St. Toronto, Ontario, M3J 1P3 and AIAA Non-Member.
[3] Associate Lecturer, School of Engineering, 4700 Keele St. Toronto, Ontario, M3J 1P3 and AIAA Non-Member.

balancing system, and complete electronics system. The air bearing system is validated using three orthogonally mounted reaction wheels. The validation process involves single axis control the reaction wheel systems to conduct slew manouvers of the sperhical air bearing system.

II. Nanosatelite Attitude Control Testbed

The nanosatellite attitude control testbed consists of a sperhical air bearing platform suspended upon a thin layer of air. The platform includes a balancing system and platform electronics. The balancing system contains both coarse and fine balancing capabilities. The electronics system includes an on-board computer (OBC), wireless transceiver, inertial measurement unit (IMU), power distribution board and batteries.

A. Spherical Air Bearing

The air bearing is a 63.5 mm diameter semi-spherical air bearing designed by Nelson Air. Air bearings are carefully designed and machined to have a precise fit to the base of the bearing. Once air passes through the bearing base, a uniform force pushes the bearing off of the bearing base. With an improperly machined bearing that does not fit precisely with the bearing base, the forces acting on the bearing are not uniform and a torque is produced as a result of the forces. A uniform layer of air creates a near frictionless surface for the air bearing to operate. A solid model of this air bearing is shown in Fig 2. Table 1 lists critical parameters of the air bearing.

This specific air bearing was selected due to its small diameter and large range of motion. Many COTS air bearings do not offer 45° roll and pitch angle capabilities[1,2]. Increased freedom of the air bearing system allows for more complex control schemes to be applied to the experiments and the air bearing system will more closely mimic a nanosatellite in orbit.

Figure 2. Air Bearing Model

Table 1. Spherical Air Bearing Properties

Spherical Air Bearing		
	Metric Units	Imperial Units
Diameter	63.5 mm	2.5”
Load Capacity	9.07 kg @ 4.08 atm	20 lbs @ 60 psi
Air Pressure Range	1.36-5.44 atm	20-80 psi
Sphere Inner Mass	0.121 kg	0.266 lbs
Inner Centre of Mass	-13.89 mm from top surface	-0.547” from top surface
Degrees of Freedom	3 degrees of rotation (roll, pitch, yaw)	
Max Angles of Rotation	45° for roll and pitch and 360° for yaw	
Material	6061-T4 aluminum with hard coated surfaces	

B. Balancing System

A properly balanced platform on the air bearing is critical to providing the torque-free test environment along all 3 degrees of rotational freedom. The payload that is to be tested is placed atop the spherical air bearing platform. To achieve torque free motion, the centre of gravity (CoG) of the system must align with the centre of rotation of the air bearing. The need for precise balancing of the test bed makes the air bearing system much more complex and design considerations are needed to ensure the adaptability to a variety of configurations.

The balancing system was designed to be as robust as possible to make the delicate balancing process as simple as possible. To secure the components to be tested, an aluminum plate is attached to the top of the spherical air bearing. The plate has a diameter of 305 mm with a thickness of 6.35 mm. This plate alone raises the centre of mass above the centre of rotation. This is shown in Table 2 and Fig 3. This demonstrates that with any components placed on the air bearing table, there must be a counterbalance in place to vertically adjust the centre of mass.

Table 2. Centre of Mass of Air Bearing with Base Plate

Configuration	Mass (kg)	Centre of Mass (mm)		
		x	y	z
Air Bearing	0.118	0	-13.854	0
Air Bearing with Base Plate	1.374	0	+1.7038	0

Figure 3. Centre of Mass of Air Bearing with Base Plate

The balancing system consists of a total of 8 threaded rods. Four rods protrude are arranged along 2 perpendicular axes in the plane of the base plate (x and y axes). The other 4 rods protrude out of the bottom of the plate and are used to lower the centre of mass along the z axis. In order to fine-tune the centre of mass, various masses may be placed along each of the threaded rods. The brackets also act as a method to secure the test subject, such as a CubeSat, on the spherical air bearing system. The brackets are place 0.1 m apart and the threaded rods may be tightened to hold the test satellite in place. The system is balanced using a combination of slotted masses and nuts which are placed along the threaded rods.

C. Electronics

The electronic hardware for the air bearing platform consists of four distinct components; the OBC, wireless communications, IMU, and power system. The OBC is a Linuxstamp II with a custom designed breakout board. The wireless communications utilize the XBee-PRO DigiMesh 900 (XBee), a small low power transceiver. The IMU is a ADIS16364 six-DOF inertial sensor. Finally, the power system consists of 2 Lithium-Polymer battery and a power distribution board to allow these batteries to be successfully integrated with the rest of the electronic system. Fig. 4 shows the complete electronics system of the spherical air bearing platform.

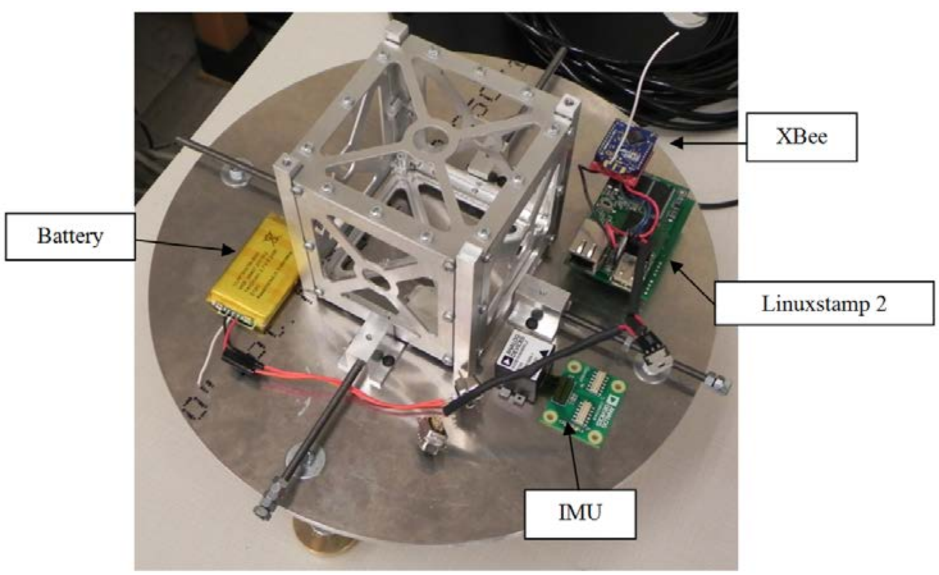

Figure 4. Electronics System

The Linuxstamp II interfaces with most peripherals through two 40 pin jumper headers at the bottom of the circuit board. These headers are extremely difficult to interface with directly and thus a breakout board was developed to utilize most functions of the OBC. This breakout board is stacked with the Linuxstamp II on standoffs.

The wireless transmitter that is used for the air bearing system is the XBee-PRO DigiMesh 900 RF Module. This module operates at a 900 MHz frequency and connects to the Linuxstamp II directly. As the main wired interface to the Linuxstamp II is a serial connection, the two data lines from the XBee are connected to the main serial interface of the

Linuxstamp II. A second XBee module is attached through the USB port of a control computer terminal. This module receives and transmits to the Linuxstamp in the same way as a standard hard connection

The IMU selected is the Analog Devices ADIS16364 Six Degrees of Freedom Inertial Sensor. The sensor consists of a tri-axis gyroscope, tri-axis accelerometers and a temperature sensor. This unit is ideal for the air bearing system as it requires minimal configuration in order to achieve substantial measurements, with minimum parasitic mass and balancing calibration. The IMU uses a serial peripheral interface (SPI) to connect to the OBC. SPI allows for parallel transmitting and receiving of data. This unit easily fits any measurement requirements for the air bearing system as detailed in Table 3.

Table 3. IMU Specifications[3]

Parameter	Value
Gyroscopes	
Maximum Sensitivity	300 °/sec
Minimum Sensitivity	0.05 °/sec
Accelerometers	
Dynamic Range	±5 *g* to ±0.001 *g*
Sampling Rate	819.2 SPS
Input Power	5 V

The IMU is able to collect measurements with a small degree of error and minimal gyroscopic drift. Table 4 examines the error obtained from a stationary air bearing platform

Table 4. IMU Measurement Error

Measurements	Standard Deviation
Roll	± 0.116577º
Pitch	± 0.121392º
Yaw	± 0.149759º
Average Gyro Drift	0.099°/s

A power distrubtion unit is designed to regulate the power to the peripherals. There are two 3.9 V lithium polymer batteries on the system. The first battery powers the electronics and a second battery powers the actuators. The first battery powers the OBC, Xbee and IMU. The OBC can operate at a voltage of 3.3 V and has an internal regulator. Thus a direct connection to the battery is acquired. The XBee requires a regulated 3.3 V and the battery connection to the XBee passes through a NTE1904 Integrated Circuit which is a 3.3 V voltage regulator. The IMU requires a constant 5 V supply and thus the first battery is also connected to an LT1111 DC/DC Converter which boosts the battery output up to the required 5 V. The second battery powers the reaction wheel system described in the following section. The motors also require a regulated 5 V supply. Furthermore, on motor start-up, the motors draw a large amount of current from the system and therefore the second battery is needed. During the start-up, the power to the OBC fluctuates and thus several 100 µF capacitors are used in conjuction with another LT1111 DC/DC converter on the power distribution unit to regulate the power. Fig. 5 details the power distribution circuit.

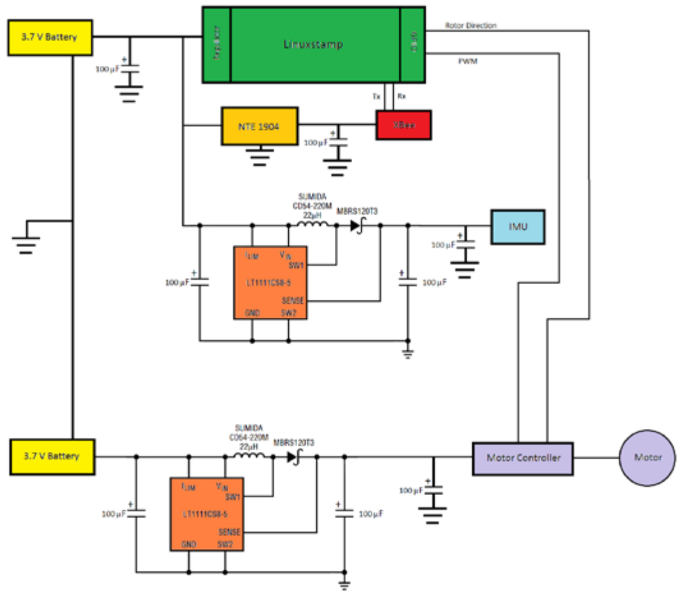

Figure 5. Power Distribution Layout

The software package for the spherical air bearing system is designed to remotely receive commands from the operator. The OBC connections to the peripheral electronics are initialized at the beginning of the test by the operator at the control station. The software is designed to output the received data to the user interface as well as record the data on the Linuxstamp II's removable microSD card. The system is designed to work in 3 different configurations. The first configuration receives a torque profile of duty cycles from the user. These duty cycles are calculated in Matlab from a torque profile on a separate machine and then loaded onto the microSD card before the test begins. The second configuration receives 3 duty cycles from the user (one for each reaction wheel) and a time for which to run the wheels. This configuration is used for constant momentum testing and for the actuator start-up. The third configuration is used for control of the sperhical air bearing system. Fig. 6 details the first 2 software options on the sperhical air bearing system. The control system will be detailed in Part III.

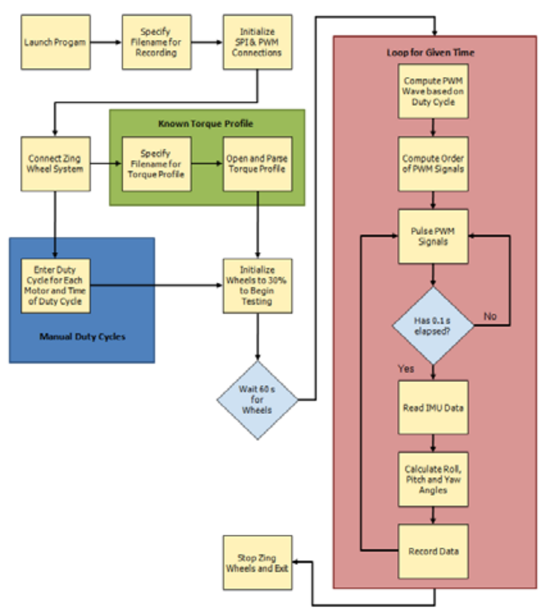

Figure 6. Software Configuration

D. Actuators

In order to actuate the air bearing system, a modular set of reaction wheel is designed and constructed. These wheels are simple motors only to be used for design demonstration. The system is design to be removed and replaced with an actual CubeSat. The reaction wheels are named Zing Wheels and are 3 orthogonally mounted reaction wheels which are mounted inside a CubeSat structure. The Zing Wheel system is comprised of 3 custom-made steel rotors, mounted upon 3 brushless DC motors. The motors are controlled by a set of drive electronics. All parts are mounted on a CubeSat structure as shown in the solid model of the Zing Wheel system in Fig 7.

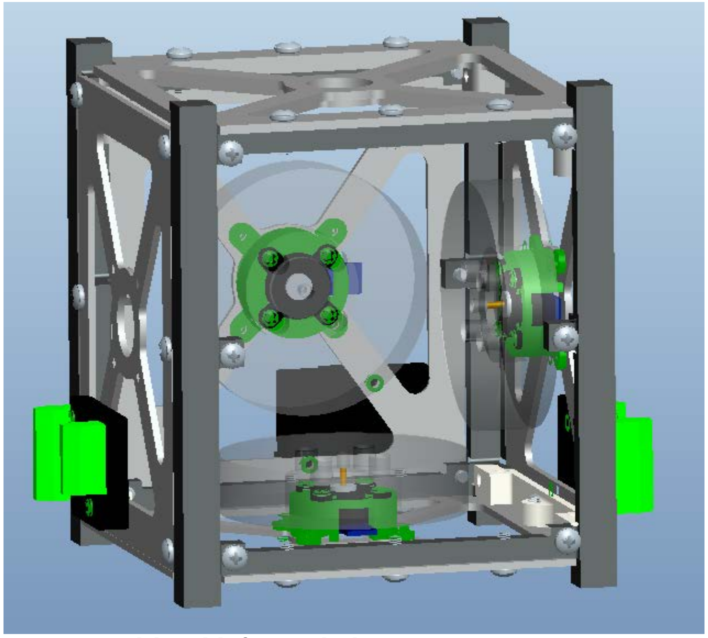

Figure 7. Solid Model of Zing Wheel System

Each reaction wheels is comprised of a steel rotor, mounted onto a brushless DC motor. The motors are Faulhaber Brushless Flat DC-Micromotors driven by a Faulhaber Speed Controller. The controller accepts a Pulse Width Modulated (PWM) signal from the OBC to drive the electronics. The speed controller offers bi-directional control and Hall Sensors for motor speed readings. The specifications for the reaction wheels and drive electronics are described in Table 5.

All components of the Zing Wheel system are mounted within a CubeSat structure. Customized motor mounts are utilized for the brushless DC motor. For a full description of the CubeSat structure used, refer to (6).

Table 5. Zing Wheel Specifications[4,5]

Specification	Value
Brushless DC-Micromotor	
Torque Produced	0.6 mNm
Angular Acceleration	14×10^3 rad/s^2
Maximum Speed (no load)	14, 700 rpm
Rotor	
Material	Steel
Mass	0.214 kg
Inertia	$\begin{bmatrix} 5.020\times10^{-5} & 0.000 & 0.000 \\ 0.000 & 9.405\times10^{-5} & 0.000 \\ 0.000 & 0.000 & 5.020\times10^{-5} \end{bmatrix}$ kgm^2
Drive Electronics	
Speed Range	500 – 30000 rpm
Input	PWM
Sensor Type	Hall sensors (digital)

III. Validation

In order to validate the sperhical air bearing system, single axis control is implemented on the platform to utilize the Zing Wheel system. A proportional-integral-derivative (PID) controller for the yaw axis to accomplish slew maneuvers of the sperhical air bearing platform.

A. Control System Design

The control system implemented on the sperhical air bearing platform is a discrete PID controller. The gains of the system were tuned using Simulink's autotune functionality and then utilized within the discrete C code. The software algorithm utilized aboard the OBC is shown in Fig. 8.

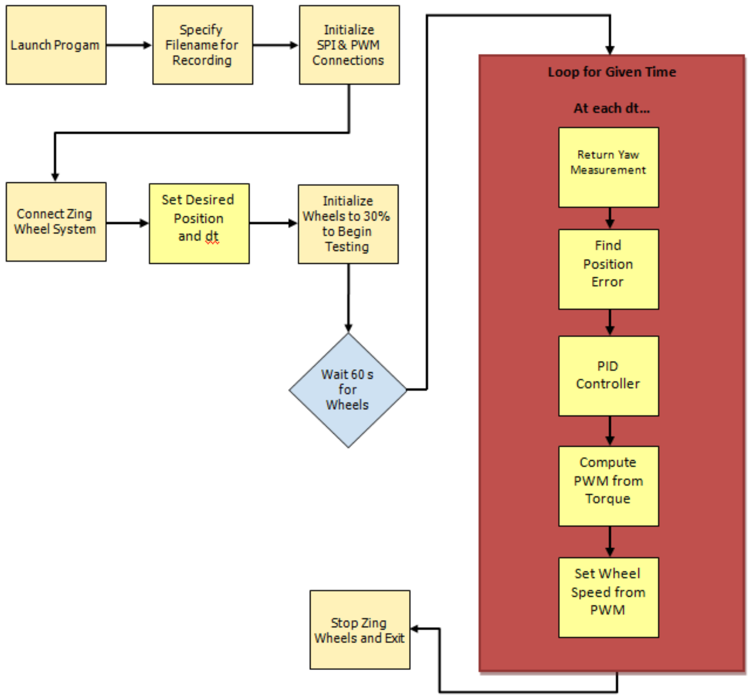

Figure 8. Control System Program

B. Lessons Learned

The limitations of the actuators alter the results of the control system. The purpose of the Zing Wheel system was to create a low-cost actuator system that could validate the spherical air bearing platform. The system is designed to be removed from the platform and replaced with a complete CubeSat in order to test proper control systems.

There are 3 limitations with the Zing Wheel system. First, the shaft diameter of the brushless DC motors have a small diameter. The Zing Wheels placed perpendicular to the gravity vector tend to bend slightly. This offset creates an imbalance in the Zing Wheel system and introduces jitter to the sperhical air bearing platform. The shaft load of the micromotor did not hold up to specicifications and the imbalanced was introduced. In order to mitigate this effect, the control system is designed to only alter the yaw angle of the sperhical air bearing platform. Another limitations is the 'dead zone' of motor operation. In the range of ±25% duty cycle, the motor is not operational and no torque is generated. As a result, smaller torques on the system are not possible. The final limitation is absence of negative torques in the positive duty cycle range. This means that when the motor goes from 30% duty cycle to 25% duty cycle, no actual torque is generated. The motor will stop producing a positive torque and allow friction to slow the rotor down on its own. The combination of these two factors limits the torque value that can be generated from the Zing Wheel system. Future work will examine these limitations and design a control system to mitigate the limitations.

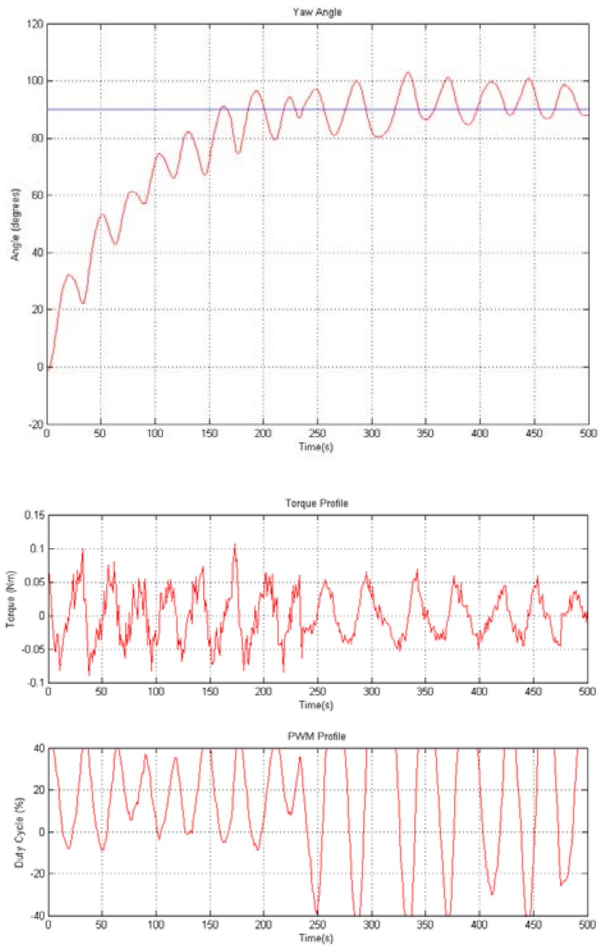

Figure 9. Results of PID Control

C. Results

The developed PID controller is used to undertake a 90° slew maneuver of the sperhical air bearing system. Fig. 9 details the results of a 90° slew of the air bearing platform. This experiment shows the success of the air bearing system as well as the limitations of the Zing Wheels. It can be seen that the small adjustment torques that the controller attempts to provide are negligible and thus increased into larger torques due to the limitation of the Zing Wheel system. This is shown on the plots as the negative response during the slew. Once, the sperhical air bearing platform has reached its desired position, the controller achieves a 10° resting value from the desired position. This is the first controller implemented on the sperhical air bearing system and it does not consider the limitations of the actuator system. Future work will involve designing a new controller to utilize the limitations to develop more accurate control. This will be accomplished by utilizing a torque profile for the Zing Wheel system.

IV. Future Work and Conclusion

The work presented in this paper represents the initial setup and testing of the spherical air bearing simulator at York University. There are significant amounts of planned and proposed work on the simulator at this current time. With respect to design of the air bearing simulator, future work includes the upgrading of the aluminium platform to a lightweight and rigid carbon fiber to reduce parasitic mass. A remote graphical user interface is currently in development to help visualize position and body rates of the simulator platform. Furthermore, a complete torque profile for the Zing Wheel system is currently in development to help improve on the performance of the current actuators. In the future, many experiments and control schemes may be conducted on the spherical air bearing simulator. The reaction wheel system will be upgraded with more precise control and will then feature 3 axis control for more complex maneuvers. Once the actuator and control system has been fully developed, many more complex control schemes may be conducted on the simulator. The main purpose of the spherical air bearing simulator is to test upcoming nanosatellite missions. This will begin in 2012 with the complete testing of a magnetic control system for a current York University mission and will be expanded to future nanosatellite missions.

In conclusion, a spherical air bearing attitude control simulator for nanosatellites has been developed at York University. This system is comprised of a manual mass balancing system and a full electronics system. The system was validated using reaction wheels as actuators to achieve desired torques needed to emulate the motion of a nanosatellite in orbit.

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