An Open-Source Reaction Wheel System for Oregon's First Satellite

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Portland State University is developing Oregon's first orbital satellite, a 2U CubeSat, dubbed Oresat. One of the primary missions of this CubeSat is to be a vehicle for STEM outreach by sending live video space-to-ground to tracking stations built and operated by Oregon high schools. This CubeSat will use a reaction wheel system for attitude control and pointing of the onboard camera, and high-gain antenna. Details of the development of the reaction wheel ground test article, and its controller, are presented here. Finally, we also present preliminary results of attitude control testing conducted in the brief (2.1 s) free-fall environment of Portland State University's Dryden Drop Tower.

Nomenclature

$M_0^{+\circlearrowleft}$	Moment in the x-axis (N m)
T^0	Torque (N m)
θ	Angular position (°)
$\dot{\theta}$	Angular velocity(°/s)
$\ddot{\theta}$	Angular acceleration(°/s^2)
I	Moment of Inertia (N m^2)
b	Damping Coefficient (N s/m)
G	Spring Coefficient (N/m)
$COTS$	Commercial Off-The-Shelf
FDM	Fused Deposition Modeling
IMU	Inertial Measurement Unit
PWM	Pulse Width Modulation

Subscripts

x	Index for Cartesian axes
rw	Reaction Wheel
n	Motor Index
A, B, C, D	Indices for Motors A, B, C, and D

I. Introduction

Small educational satellites have been launched by dozens of universities around the United States as part of NASAs CubeSat Launch Initiative (CLSI), especially under the auspices of the Educational Launch of Nanosatellites (ELaNa) program. As of 2015 CubeSats from 29 states have flown under the program,

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however the great state of Oregon has yet to join their ranks.[1] During the summer of 2015 the Oresat project was initiated by the Portland State Aerospace Society (PSAS) to rectify this situation. PSAS is an engineering student organization and citizen science project located at Portland State University dedicated to developing low-cost, open-source, and open-hardware high-powered rockets and avionics systems with special interests in venture class launch vehicle technologies and nanosatellites.[2]

The Oresat satellite will follow the "2U" CubeSat standard.[3] A CAD render of the Oresat concept is pictured in Figure 1. The primary objectives of the project are to test several subsystems in the environment of a 400 km circular Low Earth Orbit: the "Low Gain Radio (LGR)" communication board and the highly tolerant "System Controller" board. The LGR is the main low-gain radio system based on a 436 MHz radio system using the MKW01Z128 microcontroller. The System Controller is being designed expressly for the space environment, and will include some measure of fault-tolerance and radiation hardening.

The secondary mission goal is to run an educational outreach project in the state of Oregon. Called "DxWiFi", after the Amateur Radio "Dx" code for distance, OreSat will broadcast a live video feed from space to the ground using the standard 2.4 GHz 802.11b "WiFi" protocol. DxWiFi ground stations will be built by Oregon high schools using 3D printers, COTS WiFi adapter cards, and existing augmented reality cellphone apps that track satellites.

A severely power limited (~ 1 W) S-band downlink from LEO unfortunately requires high gain antennas, both on the ground and on the space vehicle. However, in order to minimize required deployables on the space vehicle, and to provide for the general simplicity of design, construction, and operation of future ground stations, we chose a 16 turn helical with approximately 15 dBi gain. This gives a relatively broad beam width antenna, requiring pointing, but only on the order of a 5-10 degrees. Since nadir pointing will only allow a few seconds of data link, Oresat must "point and stare" at a ground station that has requested to download video. This degrees-per-second slew of the antenna (and camera) requires rapid pointing changes that magnetorquers simply can not provide. Following from this is the need for a robust system to provide attitude control for Oresat. This system will be reaction wheel based. Per PSASs open-source ethos all (non-ITAR) project development deliverables are being made freely and publicly available under a GNU GPL v2 license.[4] It is hoped by the authors, and the members of PSAS that the discourse around educational CubeSats and their design will be elevated by making the information for this project publicly available.

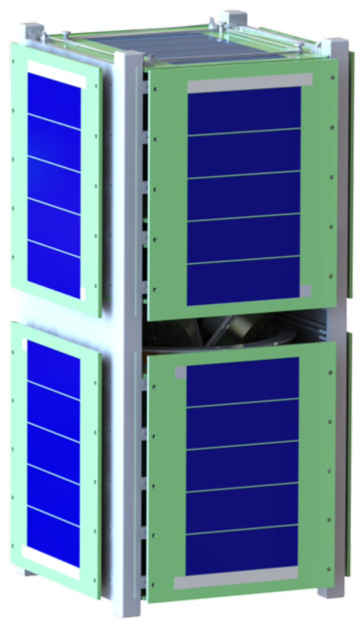

Figure 1: Speculative mockup in SolidWorks of the 2U Oresat chassis.

II. Concept Definition

Angular rate and pointing precision requirements for the flight attitude control system are determined from orbital parameters (likely those offered by Nanoracks deployment from the ISS) and the expected performance of the PSAS DxWiFi telemetry system. The ground test article is a proof of concept and uses inexpensive COTS DC brushless motors which are significantly more powerful than those required for the flight use case. The ground test article is broadly similar in design to the flight system, for example by using 4 momentum-wheels in a pyramid configuration for added redundancy and on-orbit mission assurance. Such a design is similar one recently developed for a master's thesis project at California Polytechnic State University San Luis Obispo.[5] On Oresat a magnetorquer will be used to periodically desaturate the reaction wheels by dumping accumulated momentum into the Earth's magnetic field. The other principle difference between the ground test and flight designs is that the ground test article uses the 1U form factor whereas Oresat is planned to be 2U.

III. Design and Fabrication

The Oresat reaction wheel system chassis was developed using rapid prototyping techniques over a short time period (approximately 8 weeks). This approach enables rapid design iteration cycles. A mockup 1U CubeSat structure was drafted in SolidWorks CAD, and fabricated using an FDM 3D printer. Mounted on the 3D-printed chassis are the 4X DC brushless motors, a 4-cell Li-Po battery pack, IMU shield, Intel Edison microcontroller and accompanying GPIO breakout. This 'ground' test article is shown in Figure 2. As previously noted there are several departures in the design of the ground test article from the flight system. Among these are the COTS DC brushless motors used to drive the momentum wheels; having a very high RPM limit, specifically 22,000 RPM, these motors provide substantially more torque, shaft power, and shaft speed than required by the flight system. The use of such motors is justified by the need to ground test the controllers ability to react quickly to perturbations, and to test the limits of the controller rise time. In practice, the ground test article is not constrained by requirements for power consumption, or heat generation as the flight system surely will be.

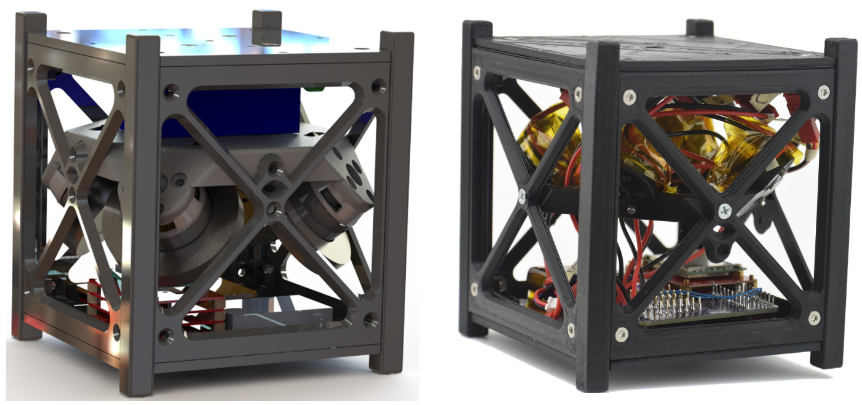

Figure 2: Reaction wheel ground test articles: a CAD render in SolidWorks, and the completed prototype.

IV. Controls Simulation and Design

The controller for the reaction wheel system is a PI loop implemented on an Intel Edison with code written in Python. The Edison receives feedback from a 9-DoF IMU over analog-in, and sends signals via GPIO to the motors. The top-level controller design procedure was as follows:

1. Determine the transfer functions from dynamics analysis of free body diagrams of the system
2. Create simulation in GNU Octave
3. Design the controller using iterative testing (with comparisons to the model) and classical Bode techniques

The transfer functions are determined with a dynamics analysis of the free body diagram, shown schematically for a single axis in Figure 3. The forces acting on the cube are the torques created by the motors T_i^0, damping effects $b_1\dot{\theta}_{cube}$, and spring effects $G_1\theta_{cube}$. Summing the moments around the center of gravity gives the following equation:

$$\sum M_0^{+\circlearrowleft} = I_{x,cube}\ddot{\theta}_{x,cube} = T_{Ax}^0 + T_{Bx}^0 - T_{Cx}^0 - T_{Dx}^0 + T_x^0 - \dot{\theta}_{x,cube} - G_x\theta_{x,cube}. \tag{1}$$

Solving Eqn. 1 so that θ_{cube} and its derivatives are on the left side, and the motor torques are on the right side, as well as setting the system to Standard Equilibrium Position (at SEP the input perturbations are set to zero) and substituting the torque-inertia relation we have

$$T_x^0 = 0,$$
$$T_{nx}^0 = I_{rw}\ddot{\theta}_n.$$

This gives us the following equation:

$$I_{x,cube}\alpha_x + b_x\dot{\theta}_{x,cube} + G_x\theta_{x,cube} = \sin(45°)I_{rw}(\ddot{\theta}_A + \ddot{\theta}_B - \ddot{\theta}_C - \ddot{\theta}_D).$$

Per the textbook definition of a transfer function we have the output of a system with respect to a single input, so all motors are set to zero except for one (A for this example). Applying a Laplace transform to the previous equation we have

$$\frac{I_{x,cube}}{\sin(45°)I_{rw}}\theta_{x,cube}s^2 + \frac{b_x}{\sin(45°)I_{rw}}\theta_{x,cube}s + \frac{G_x}{\sin(45°)I_{rw}}\theta_{x,cube} = \theta_A s^2.$$

Finally moving θ_{cube} and θ_A to the left side of the equation and everything else to the right, we arrive at the transfer function describing the system:

$$G_A(s) = \frac{\theta_{x,cube}(s)}{\theta_A(s)} = \frac{s^2}{\frac{I_{x,cube}}{\sin(45°)I_{rw}}s^2 + \frac{b_x}{\sin(45°)I_{rw}}s + \frac{G_x}{\sin(45°)I_{rw}}}. \tag{2}$$

Using the transfer functions, given schematically for one axis by Eqn. 2, a simulation was created in GNU Octave which yielded step response plots shown in Figure 4. The simulation model will further aid in Bode analysis for the determination of stability margins which relate the frequency response of the system to its time response. The margins can be adjusted with the use of a controller to affect the time response characteristics of the system. In the case of the ground test system we expect the rise time for a 90° step input to be under 1 second.

V. Controller Testing and Results

A unique and exciting testing opportunity involves exploiting the high-quality μ-gravity environment of Portland State University's Dryden Drop Tower (DDT) facility for free fall tests of the reaction wheel system. The Dryden Drop Tower, patterned on the 2.2 Second Drop Tower facility at NASA's Glenn Research Center in Cleveland, Ohio, is optimized for exceptionally fast drop turnaround times. The DDT is one of the most

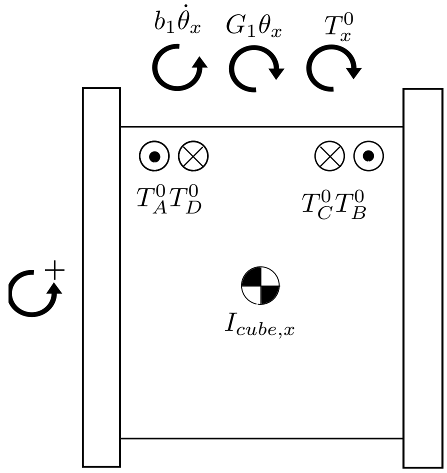

Figure 3: Free Body Diagram of the CubeSat in the Cartesian x-axis.

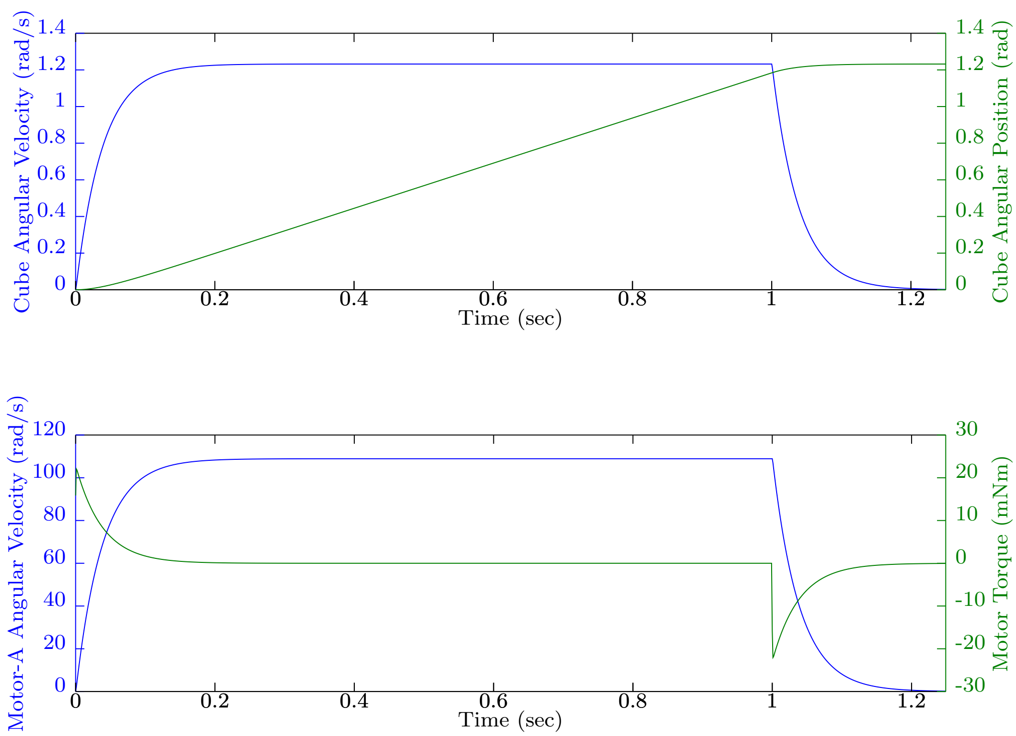

Figure 4: CubeSat step response compared with singular motor response.

productive drop towers in the world for its class, with more than 5800 drops over its 6 year history. The DDT's 2.1 seconds of free-fall conditions provide unique opportunities for the observation of phenomena that are usually masked at the macro-scale in 1-g gravity fields. The relative quality of the μ-gravity environment of a drop tower is very high compared to those offered by parabolic flights (generally 10^{-5} or 10^{-6}-g for the drop tower compared to 10^{-1} or 10^{-2}-g for a parabolic flight). In this relatively high quality μ-gravity the CubeSat attitude control system can be tested in an environment similar to that of outer space (at least in an inertial sense). In the DDT the reaction wheel system testing program involved a random (25

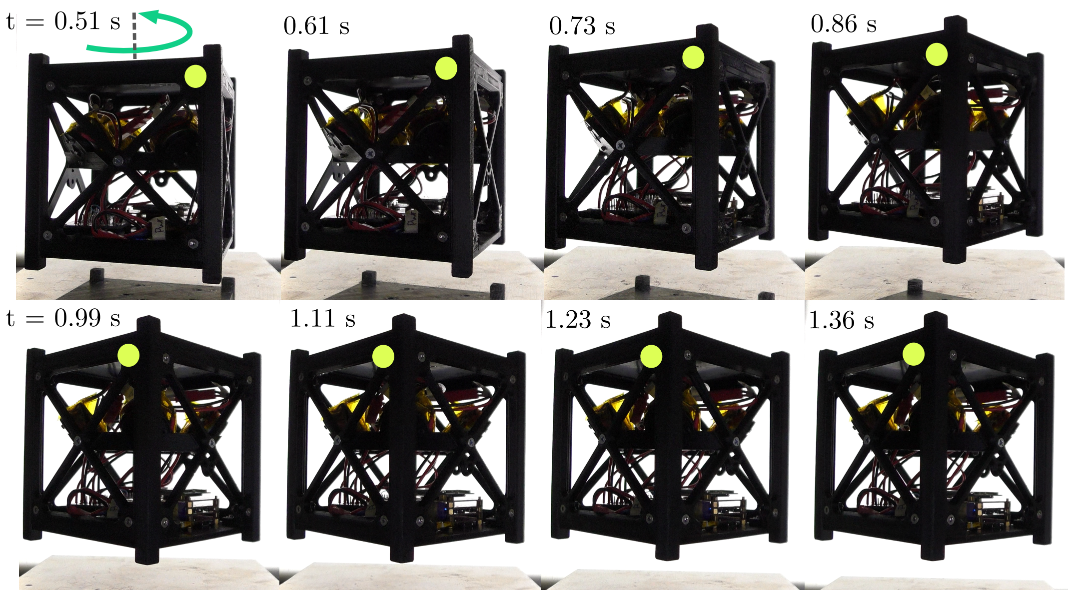

Figure 5: Time lapse of the CubeSat controller drop tower test. Initial roll impulse damped to 0 rad/s in approximately 1.9 s. The light green dot locates a fixed reference point on the CubeSat chassis. The rotation of the CubeSat, as viewed from above, is clockwise.

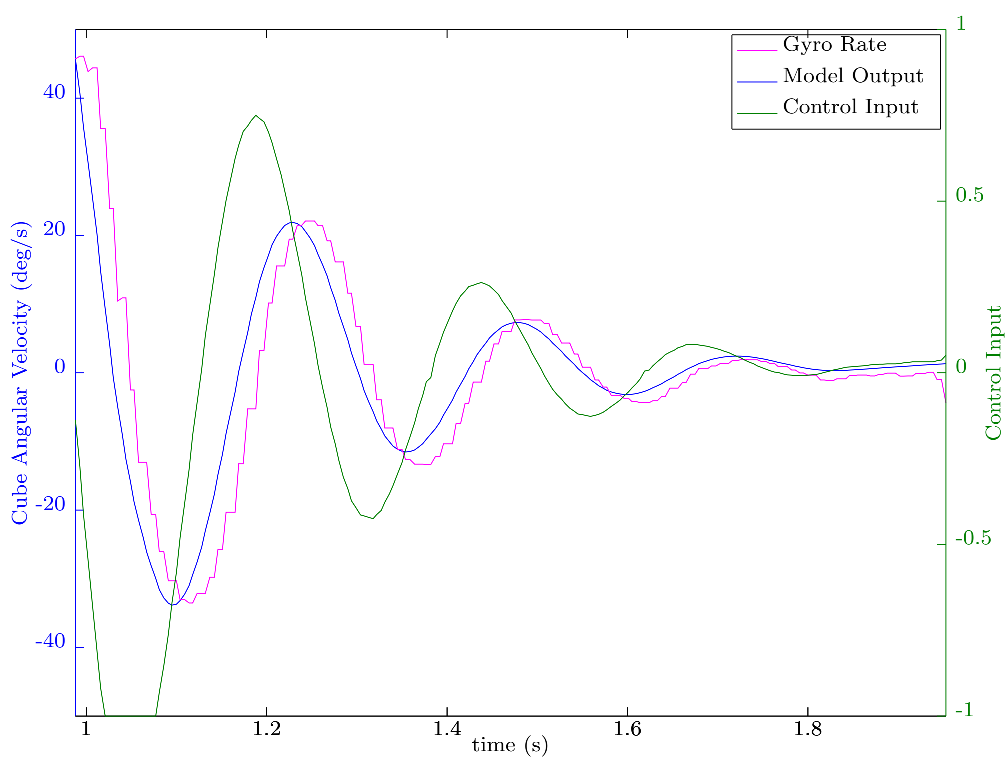

Figure 6: Drop tower test 1-DoF gyro data for z-angular rates (in pink) compared to the rates predicted by the controller model (in blue). The gyro data is presented here in an unfiltered form.

% duty cycle PWM) perturbing impulse followed by a command to damp this roll in the brief Cinderella-like moment before 1-g gravity returns 2.1 seconds later. A time lapse image of the CubeSat, showing the initial roll impulse and subsequent damping is presented in Figure 5. On a qualitative examination of the simulated roll response compared to the experimental gyro rates from the IMU, the model appears to in strong agreement (in terms of the frequency and damping ratio) with the actual physical system, at least for this particular impulse. This is shown in Figure 6. The 0.03 s phase shift between the gyro data and the angular rates predicted by the simulation may be due to the discrete time lag of the physical controller, and also to the small amount of damping by aerodynamic drag.

Following from the first test, an initial modicum of model validation allows us to continue with the model as the basis for further iterative controls testing. We plan to select a series of additional test points to formulate a more complete Bode diagram; this will require drop tests at several additional frequencies. Once the Bode diagram is completed a new model can be backed out, and the iterative controller design loop can be started anew. This work is in progress (as of August, 2016), and should be completed before the Oresat Critical Design Review in November, 2016 which is concurrent with the next round of NASA ELaNa proposals.

VI. Acknowledgments

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