A Low-Cost Method for Reaction Wheel Torque Characterization in Small Satellites

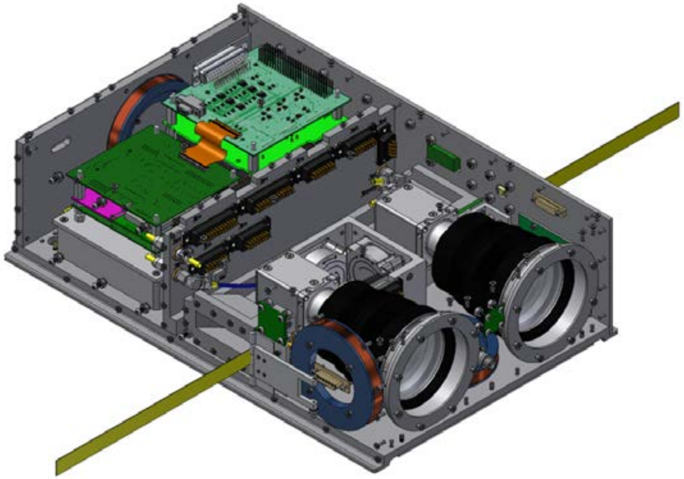
Seamus Lombardo
Dr. John Crassidis (PI)
University at Buffalo (SUNY)

Cubesat Programs

- Small Satellite industry continues to grow as the potential of Cubesats is realized
- University Cubesat programs also continue to grow
  - University Nanosatellite Program (AFRL)
  - Undergraduate Student Instrument Project (NASA)
- Fantastic learning opportunity
- Increasing mission benefits
  - Space Situational Awareness
  - Imaging
  - Science
  - Technology demonstration
- Small Satellite programs must maintain low budget

UBNL: GLADOS

- University at Buffalo Nanosatellite Lab is part of AFRL and NASA cubesat programs
- Glint Analyzing Data Observation Satellite (GLADOS) is an SSA mission that seeks to gather glint data on space debris
- Tracking objects in GEO from LEO requires fine attitude control
  - Reaction wheels provide this control
- Sought to characterize the torque of GLADOS's MAI 101 reaction wheels to validate torque resolution requirements
  - Particularly interested in low torques for tracking maneuvers



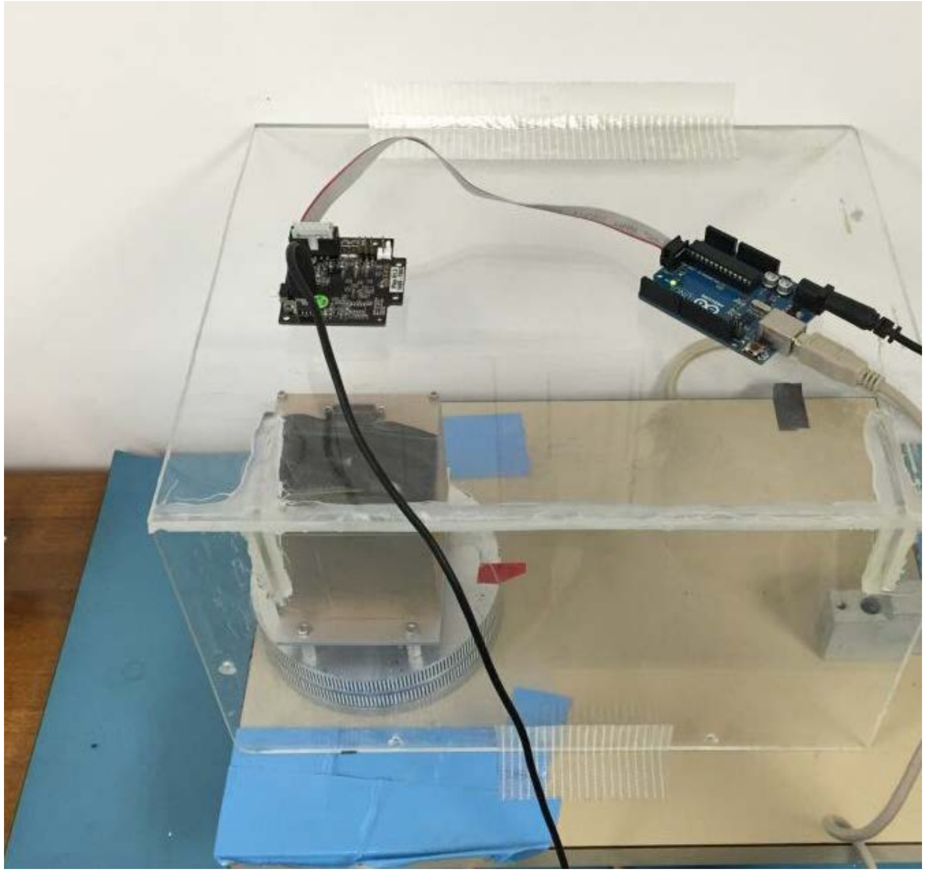
* Glint – specular reflection off of flat surfaces

UBNL Test Procedure Outline

- Place MAI 101 reaction wheels on spin table and command torque to the wheels
- Use a Pixy Camera to track the angular position of the table with respect to time
- Use the position data (θ_m) to obtain angular acceleration (α_m) of the table
- Use acceleration along with inertia to obtain torque output by the wheels
  - $\tau_m = I\alpha_m$
- Compare measured torque to commanded torque to obtain torque accuracy
  - $\frac{\tau_m}{\tau_c} = \tau_{\%}$

Test Setup

- Place reaction wheels on standard air bearing spin table
- Place electronics on top of wheels to provide power and wireless communication
- Mount Pixy camera facing down over the spin table so that a colored marker on the table edge can be tracked
- Command a torque to wheels
- Use Arduino Uno and laptop to capture x and y position data of marker in Pixy camera frame



Methodology: Calibration

- To obtain angular position data, relative center of x and y coordinates must be found
- Marker is tracked through a full rotation so maximum and minimum coordinates are obtained
- Using coordinates and physical measurements, data is processed into a relative coordinate frame with origin at center of x and y range
- Position data in this frame exhibits sinusoidal shape, indicative of accurate characterization of circular spin table

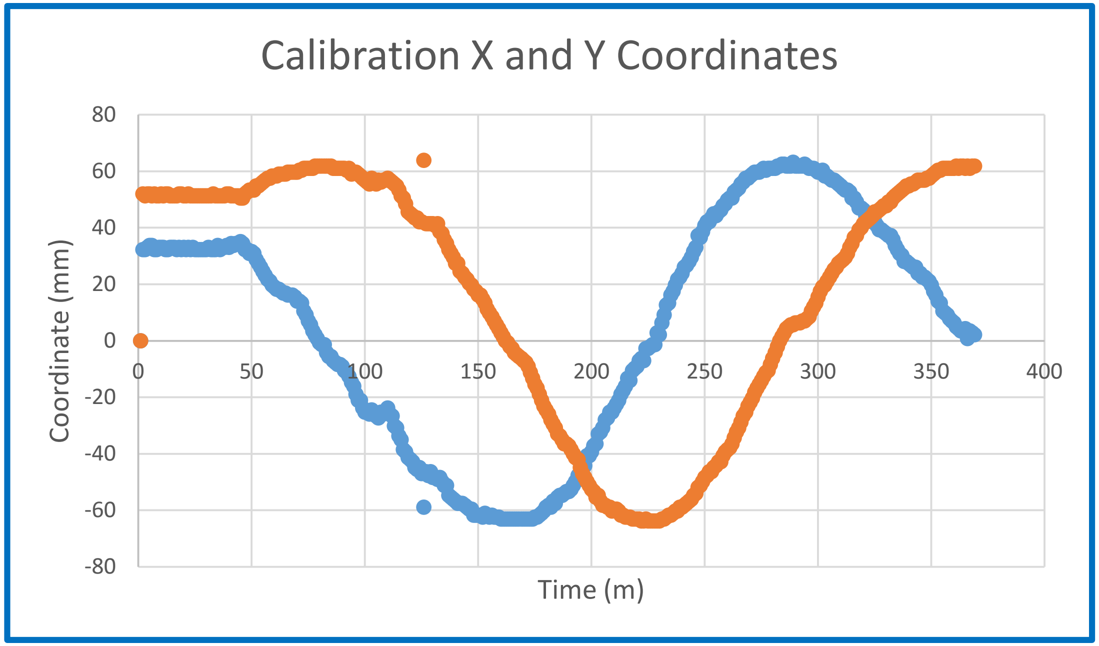


Figure 1: Calibration

Methodology: Inertia Determination

- Completely experimental method preferred, discussed in improvements
- Formula to obtain torque is $\tau_m = I\alpha_m$ therefore inertia must be determined
- Used $H = I\omega_m$ (Momentum storage capacity listed on data sheet)
- Wheels commanded to ω_{max} and angular position data recorded
- First order section of curve representative of angular velocity when the momentum is at the saturated data sheet value
- Value of inertia used for all trials ($I = 2.0x10^3 kg - m^2$)

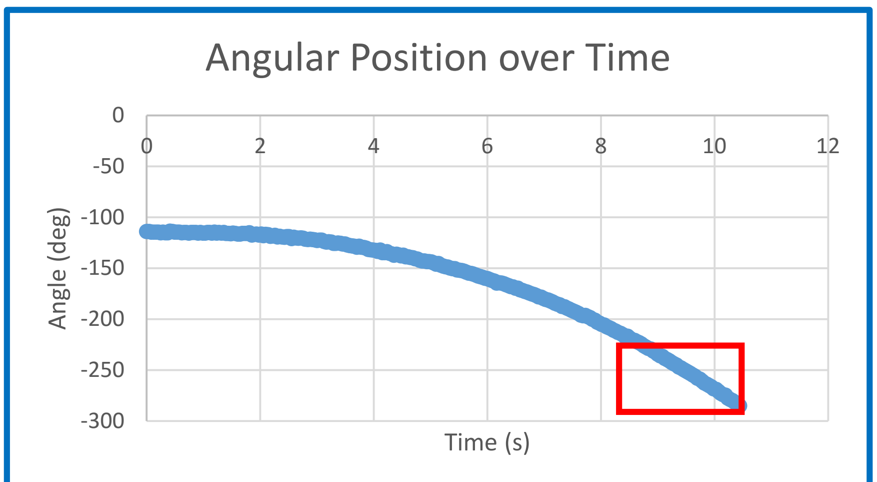


Figure 2: Position Data – Inertia Trial

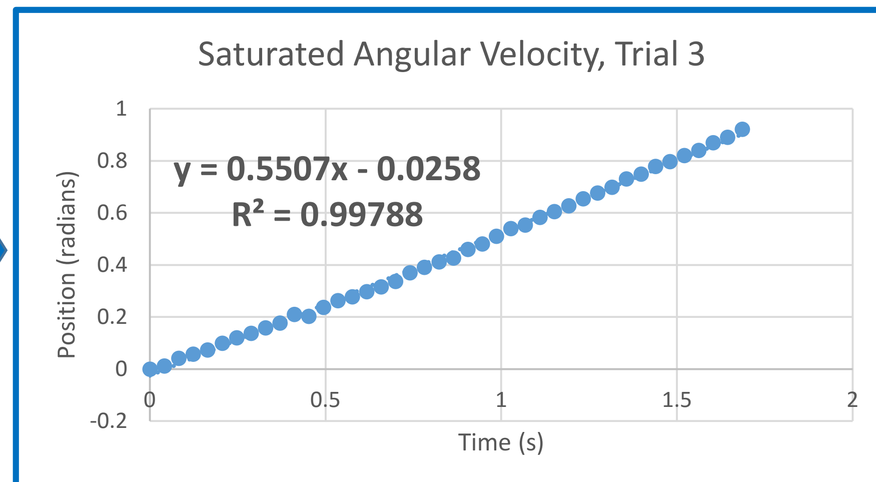


Figure 3: Saturated Period – Inertia Trial

Methodology: Torque Verification

- Torque commanded to wheels, and angular position data of marker obtained
- Acceleration period extracted
  - Start marked by rise from constant value
  - End marked by transition from 2nd order to 1st order
- Second order polynomial fit to normalized position data
- Assuming constant acceleration, $\theta = \frac{1}{2} \propto t^2 + \omega_0 t$
- Table at rest, $\omega_0 = 0$
- Coefficient of squared term in polynomial fit is used to calculate angular acceleration
- Angular acceleration and inertia are used to calculate torque

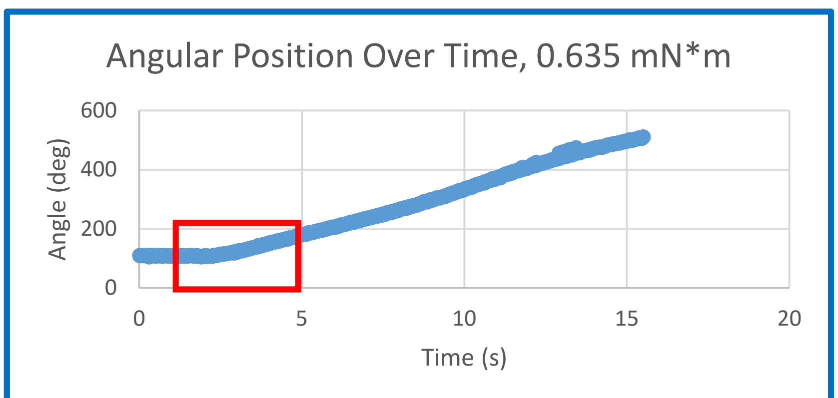


Figure 4: Position Data Example

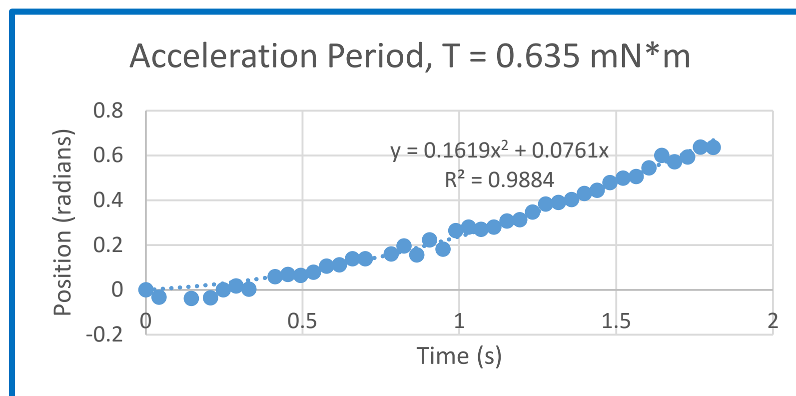


Figure 5: Acceleration Period Example

Trial Walk-through

- Torque of 0.635 mN-m commanded to wheels and angular position data obtained

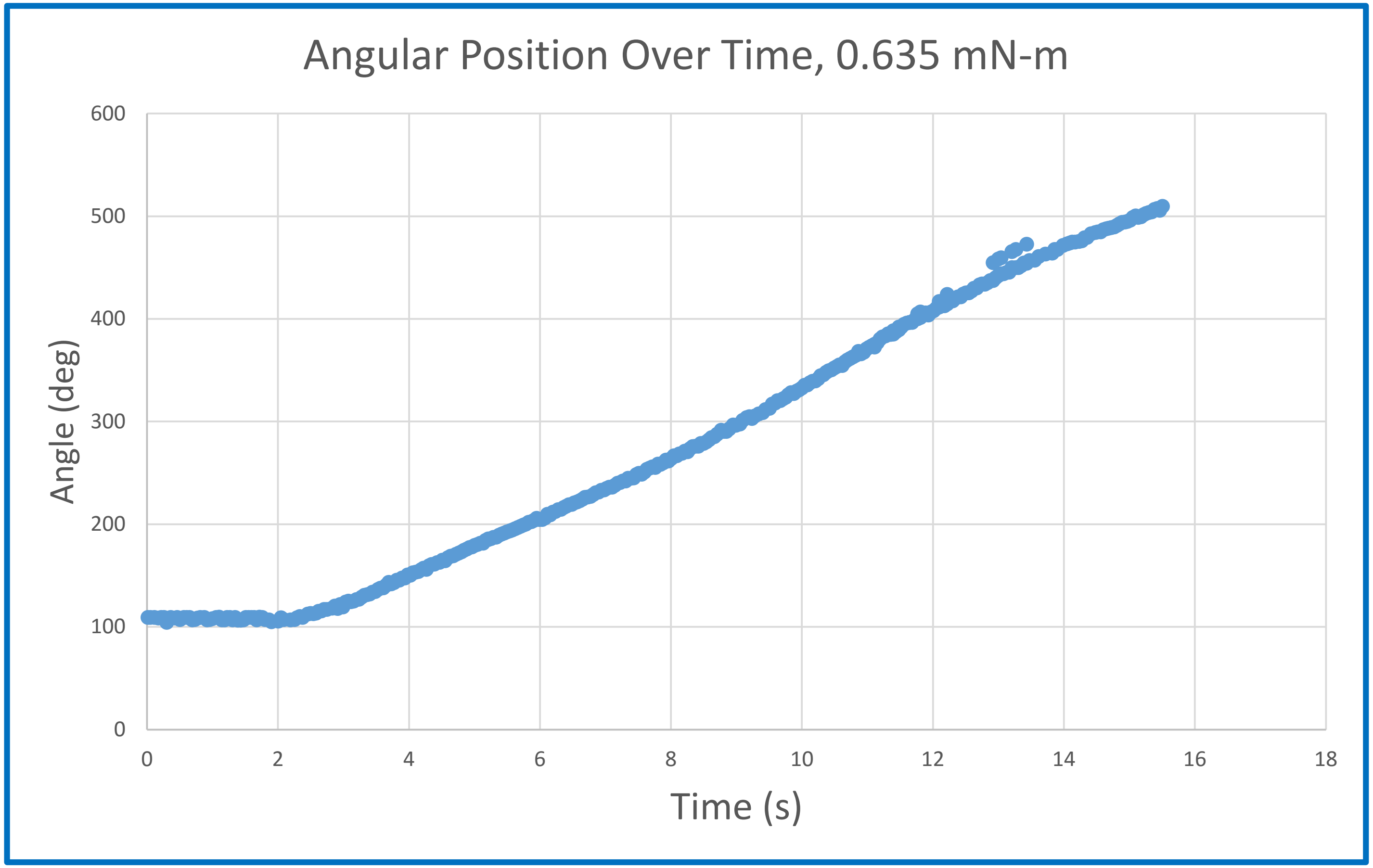


Figure 6: Position Data 0.635 mN-m

Trial Walk-through

- Examination of data determined acceleration period is from 2.044 to 3.853 seconds
- Normalized time and position data are then plotted
- Second order polynomial fit to data

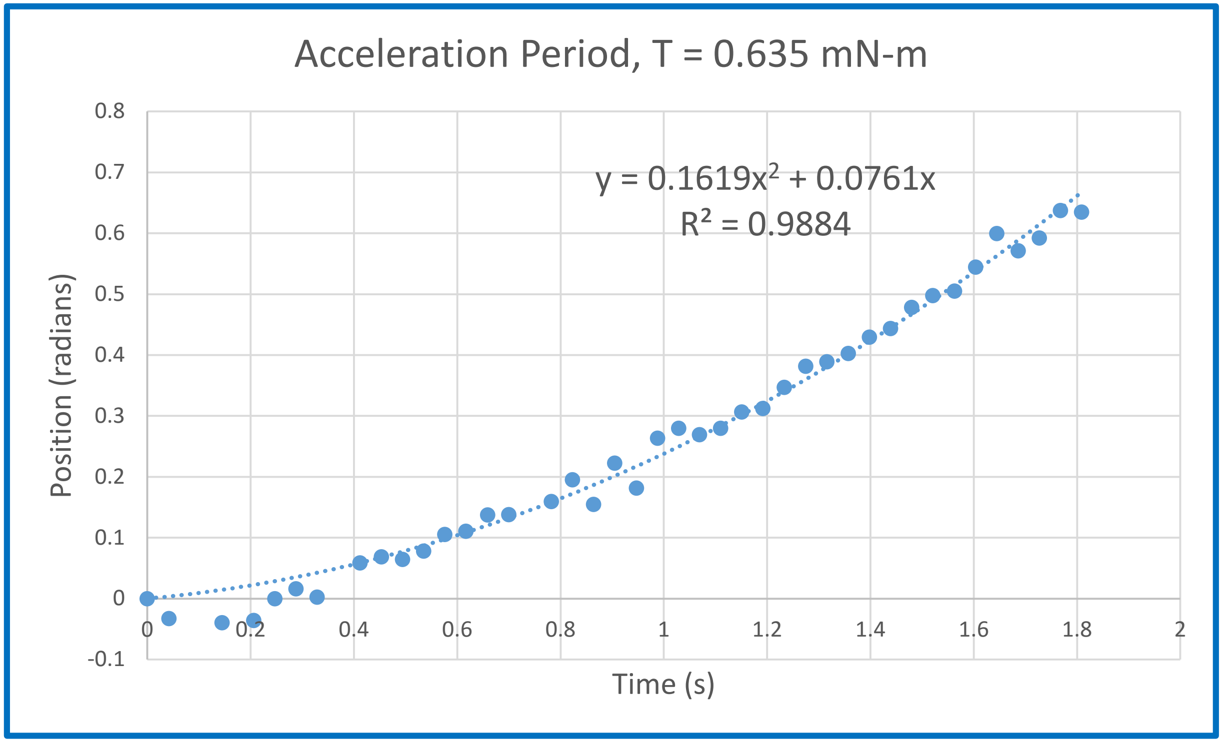


Figure 7: Acceleration data 0.635 mN-m

Trial Walk-Through

- Squared term is 0.1619
- $\tau_m = I\alpha_m = 2.0x10^3 * 2 * 0.1619 = 0.647\, mN - m$
- For purposes of test applied torque was divided by commanded torque as success metric
- $\frac{\tau_{applied}}{\tau_{commanded}} = \frac{0.647\, mNm}{0.635\, mNm} = 101.95\%$
- For purposes of presentation R^2 from curve fit (Excel generated) will be success metric
- Indicates on scale from 0 to 1 how well angular position data can be fit to second order curve to determine angular acceleration

Results

- High R^2 values for all trials
- R^2 values high even for trials in which torque percentage is low
- Indicates setup can accurate obtain angular acceleration

$Trial$	τ $commanded$ (mNm)	τ $measured$ (mNm)	τ percentage (%)	R^2
1	0.191	0.169	88.7	0.999
2	0.254	0.254	75.3	0.999
3	0.318	0.36	113.5	0.972
4	0.381	0.38	99.6	0.985
5	0.445	0.454	102.1	0.989
6	0.508	0.517	101.7	0.984
7	0.572	0.522	91.4	0.994
8	0.635	0.647	101.9	0.988

Table 1: Results from all trials

Results

- Lowest R^2 value is 0.972
- Arduino data output rate decreased in this trial
- Less data to fit to curve
- Still has high R^2 value, and bears resemblance to second order curve
- In future trials, Arduino data can be checked for gaps immediately after trial

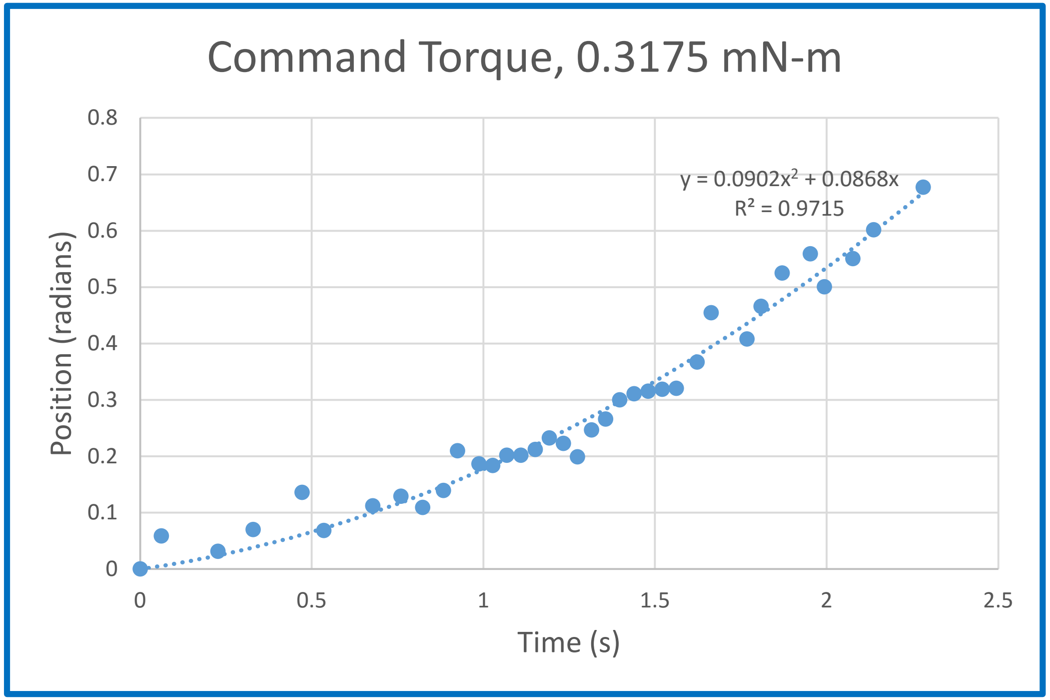


Figure 8: Acceleration data 0.3175 mN-m

Results

- Some trials exhibit low torque percentages; bears further examination
- Trial 2 has torque percentage 75%, but R^2 value of greater than 0.99
- No data resolution issues
- Effect of changing time of acceleration does not effect percentage value
- Indicates inability of reaction wheels to carry out commanded torque
- If inertia or friction were affecting results, it wouldn't manifest only at low speed
- Same for similar trials

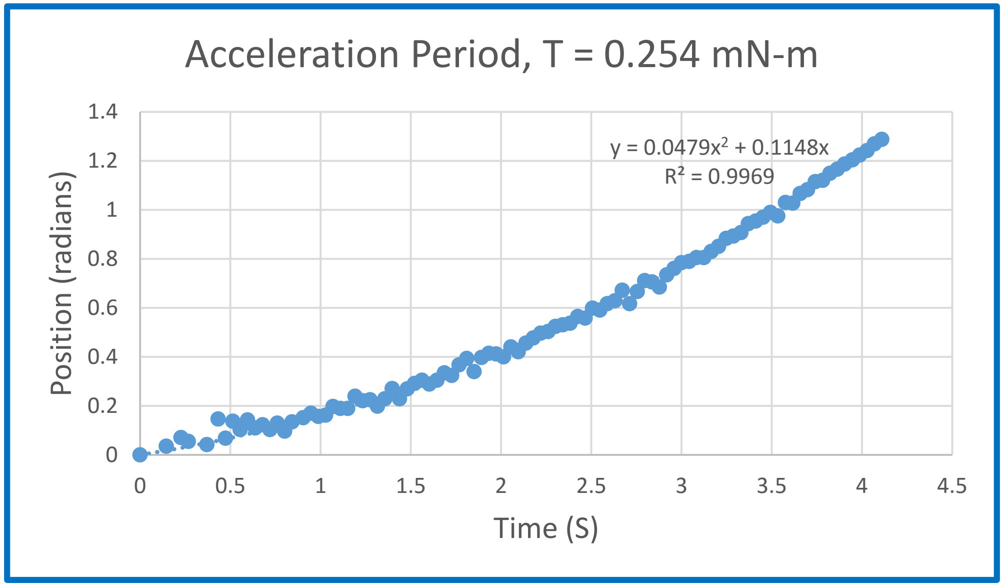


Figure 9: Acceleration data 0.635 mN-m

Advantages

- Minimal hardware development
  - No complicated force tables
- Minimal software development
  - no EGSE or data acquisition systems necessary
- Potential for increase in data fidelity over wheel-speed testing
  - Tachometery methods required detail knowledge of wheels inertia or assumptions – difficult with packaging
  - Spin table setup affords easier inertia characterization when calculating torque
  - Wheel speed can be difficult to measure independently
  - No issues with obtaining measurements

Advantages

- Cost is high priority for Cubesat programs and all Aerospace industry partners
  - No development costs
  - Low time commitment
  - Pixy+Arduino is under $100
  - Kistler tables used in industry can cost ~$40000
  - IRAD project at NASA Goddard for purpose of measuring reaction wheel torques in cubesats currently at ~$19000
  - Provides extremely cheap alternative for first-pass characterization

Future improvements

- Improve frictionless assumption
  - Improve characterization of wheels center of mass to prevent dragging
- Experimental method of inertia determination
  - Use pulley
  - Would be enabled by strengthening spin table
- Precise timestamping of commands
- Characterize error inherent in Pixy
  - Further research into machine vision required

Conclusions

- Low cost wheel characterization needed for small satellite projects
- Pixy cam was able to characterize angular acceleration, and therefore torque, with high degree of accuracy
- Setup has many benefits
  - Minimal development
  - Potential for detailed characterization given improvements
  - Order of magnitude lower cost

Acknowledgements

- Nick Digregorio, Mara Boardman, Andrew Harris, Maura Sutherland, and Luke Joy for their help with the original test
- Dr. John Crassidis for his constant support of UBNL
- NASA USIP and AFRL for their support of our lab
- The staff at NASA Goddard Space Flight Center for providing me with insight into current testing practices

References

- Ismail, Z., & Varatharajoo, R. (2015). Reaction Wheel Configurations For High and Middle Inclination Orbits. *ARPN Journal of Engineering and Applied Sciences, 10*(21). Retrieved April 9, 2016, from http://www.arpnjournals.org/jeas/research_papers/rp_2015/jeas_1115_3023.pdf
- Hur-Diaz, S., Wirzburger, J., & Smith, D. (2008). Three Axis Control of the Hubble Space Telescope Using Two Reaction Wheels and Magnetic Torquer Bars For Sciences Observations. *American Astronomical Society*. Retrieved April 10, 2016, from http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080023343.pdf
- Buchen, E., & DePasquale, D. (2014). 2014 Nano / Microsatellite Market Assessment. Retrieved April 9, 2016, from http://www.sei.aero/eng/papers/uploads/archive/SpaceWorks_Nano_Microsatellite_Market_Assessment_January_2014.pdf
- Lukaszynski, P. (2013). *Attitude Control Hardware and Software for Nanosatellites* (Unpublished doctoral dissertation). University of Toronto.
- Sanders, D., Heater, D., Peeples, S., & Sykes, J. (2013). Pushing the limits of Cubesat Attitude Control: A Ground Demonstration. *AIAA/USU Conference on Small Satellites*. Retrieved April 9, 2016, from http://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=2932&context=smallsat
- Crowell, C., & Miller, D. (2011). *Development and Analysis of a Small Satellite Attitude Determination and Control System Testbed* (Unpublished master's thesis). Massachusetts Institute of Technology. 1.
- Hoevenaars, T., Engelen, S., & Bouwmeester, J. (2012). Model-Based Discrete PID Controller For Cubesat Reaction Wheels Using COTS Brushless DC Motors. International Academy of Astronautics - American Astronomical Society. Retrieved April 16, 2016, from http://www.lr.tudelft.nl/fileadmin/Faculteit/LR/Organisatie/Afdelingen_en_Leerstoelen/Afdeling_SpE/Space_Systems_Engineering/Publicaties/2012_IAA_Hoevenaars_Engelen_Bouwmeester_V01-_284637.pdf
- Hudek, J. D. (2016, February 18). ACS System Torque Measurement Inquiry [E-mail].
- Hudek, J. (2016, July 08). Cubesat Torque Measurement Techniques [Telephone interview].