Introduction:

The overall goal of the NASA Microgravity project is to provide a low-cost alternative to current microgravity testing procedures for space-bound objects. The microgravity project examines a novel idea. The expense and wait lists that come with other microgravity testing methods creates a market potential for this modular system. The aim of the microgravity project is to achieve a microgravity environment though the free-fall of a monocoque containing a testing compartment for CubeSats. The higher the quality of the microgravity environment, the more customers will pay for the testing services. The Controls Group focused on using a reaction wheel system to stabilize the package during free-fall, improving the quality of the microgravity environment.

Background:

A weather balloon attached to the monocoque will carry the package to an elevation of 100,000 ft. As the package reaches the altitude at which the drop will occur, the monocoque may be swinging from the line that connects it to the weather balloon. In order for the first few seconds of the drop to achieve the best possible quality of microgravity, the aerobody should be oriented normal to the earth and the accelerations on the package minimized before release.

As the aerobody falls through the atmosphere and speed of the monocoque increases, the aerodynamic forces on the body will also increase. Imperfections in the monocoque composite, flaws in the fins, or the alignment of the fins could cause forces at higher velocities. It is also important to consider forces on the aerobody caused by wind. These forces could affect the quality of the microgravity environment; if one of these forces causes the aerobody to start tumbling about any axis this might ruin the microgravity environment. To maintain microgravity that is comparable to current testing services, the rotational and centripetal accelerations need to be limited.

\[ a_R = R \omega^2 \]
\[ a_\theta = R \dot{\omega} \]
\[ a = \sqrt{(R\omega^2)^2 + (R\dot{\omega})^2} \leq 10^{-3} \]

In order to correct for forces on the package, as well as imperfections that may occur in the manufacturing process, a control system is necessary to ensure that accelerations do not exceed acceptable values.

**Objectives:**

The Controls Group has a primary goal of investigating the use of reaction wheels to maintain a quality microgravity environment below \(10^{-3}g\). Critical to this goal is controlling rotation about the z-axis, normal to the Earth’s surface, while falling. This project focuses on creating a reaction wheel system that counteracts z-axis rotation and maintains acceptable microgravity.

**Design Constraints:**

For the project to be successful it must not only achieve the above objectives; it must do so while working under the constraints imposed by the overall design considerations. Perhaps the most important considerations are those that relate to both the size and weight of the drop package. The current design has very little available space. Within the monocoque is a structural frame, the CubeSats, a parachute, and the electronic systems used for collecting and relaying sensor data. This leaves about a 10 cm square with a maximum clearance of 5 cm of space between the frame and the monocoque shell for the x and y axis reaction wheels and similar space constraints within the frame for the z-axis reaction wheel. Secondly, there are strict guidelines that regulate the total weight of the testing apparatus, as well as each individual component of the assembly. The actual drop package must remain under six pounds (2.72 kg) per FAA regulations. Lastly, it is important that the system design require low power consumption. Batteries selected must fall within the size and weight constraints previously defined. Appendix A contains a total mass budget of the current control system. The table below shows a summary of design constraints:

<table>
<thead>
<tr>
<th>Nasa Microgravity Senior Design Project</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Controls Group</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motor</th>
<th>Microcontrollers</th>
<th>Reaction Wheels</th>
<th>Battery</th>
<th>Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature: -60°C</td>
<td>Temperature: -60°C</td>
<td>Diameter: 10 cm</td>
<td>Temperature: -60°C</td>
<td>Temperature: -60°C</td>
</tr>
<tr>
<td>Motor Controller: Necessary</td>
<td>Communication: digital</td>
<td>Depth: 2cm</td>
<td>Voltage: 12V</td>
<td>Resolution: &gt;10^-3g</td>
</tr>
<tr>
<td>Weight: 0.34 kg</td>
<td>Clock Speed: ~16MHz</td>
<td>Weight: 0.45 lbf</td>
<td>Max Current Dissipation: Motor Dependent</td>
<td>Communication: Digital</td>
</tr>
</tbody>
</table>

| PWM pin: 3 | Production Method: UW Shop | Watt-hours: 12V@1.5A for 1 min | 0.5-0.75 Whr | Sensors in Package |
| Digital Pins: ~10 | Weight: 0.23 lbf | DOF: 3-axis | | Accelerometer gyrosopes magnetometer |

**Table 1**

**Safety Considerations:**

The main safety concern of the microgravity project as a whole is the possibility of an unchecked free-fall. This would occur if an internal failure inhibited the deployment of the parachute. The controls group’s reaction wheel system is critical to maintaining a quality microgravity environment, yet must not negatively affect the parachute release. If the reaction wheel underwent a critical failure, the flywheel may possibly separate from the mounted motor.
The internal frame prevents a loose flywheel from reaching the pyrotechnic system governing the parachute deployment because the wheel is too big to fit through any of the gaps in the frame. After analyzing the different failure modes of the reaction wheels, any sort of failure could result in the breakdown of the microgravity environment (See Appendix B). If this were to occur, it may result in a failed test but would not be a risk to public safety.

**Economics:**

As part of the NASA Microgravity Project, the budget for this project is included in the NASA grant. Reaction wheels are by no means a new design, and are widely used by industry for control; especially in satellites, telescopes and similar systems. Despite this, the industry is specialized with stringent requirements for high-quality products, making commercially available reaction wheels prohibitively expensive for this project as well as being impractical because of their scenario specific designs. Compared to buying a system, the custom reaction wheel designed during the course of the project was relatively inexpensive. The main expenses in this project were motors and electronic sensors, which vary greatly in terms of quality and cost. The sensor package costs approximately thirty dollars and the selected motor package costs approximately five hundred dollars with all necessary components. Total expenses of a custom reaction wheel system were much less than any commercial system available; Appendix C contains the total expense in the project expense record.

**Fins:**

The current aerobody has a boom and fin assembly attached to the rear with the purpose of moving the aerodynamic center toward the rear, resulting in increased stability. One option proposed at the beginning of the project was to implement movable control surfaces in the fins as a control system; however, due to low air density in the drop environment this method of control would likely be ineffective. Furthermore, implementation of controllable fins is impractical given the space restrictions of the boom. The boom does not contain enough space to house motors and any control system would complicate the fin alignment process. Because of this, control system design focuses on a reaction wheel system.

**Reaction Wheel System Overview:**

In its simplest form, the reaction wheel has three basic components. A flywheel gives the system rotational inertia and momentum. A motor provides the necessary torque to the flywheel, and in turn a reaction onto the package itself. An electronic system must collect sensor input data about the package’s attitude in order to control the motors to make adequate corrections. Finally, a control system, such as a proportional-integral-derivative (PID) control loop, translates system inputs from the sensor into outputs to the motor in order to drive the reaction wheel.

**Flywheel:**

Given the design constraints applied to the flywheel, it requires large rotational inertia and minimal overall weight. Both the maximum angular velocity and polar moment of inertia of the flywheel affect the ability of the reaction wheel to correct force inputs. Based on nominal motor speed the flywheel must withstand stresses induced at 5000 RPM.

The z-axis flywheel, mounted within the frame rather than on the outside, differs in design from those of the x and y-axes. Finite element analysis, used to design each flywheel, allowed for removal of unneeded material from the spokes and optimization of the moment of...
inertia. Frame dimensions constrain the z-axis reaction wheel a radius of 4.75 cm. This analysis also designed the flywheel with a profile deep enough to house the motor inside (Figure 2).

Results of the analysis found that the spokes of the reaction wheel could be less than 2mm for all reaction wheels. A 2mm spoke design required 4340 steel for the flywheel to account for heat stresses encountered during machining. The University of Wyoming machine shop produced the z-axis reaction wheel used for prototyping in this project (See Appendix D for Shop Drawings).

Modifications to the original design added a hub to the flywheel to increase contact between the spindle of the motor and the flywheel. This modification inhibited recessing the motor into the flywheel. For the z-axis, this is not a problem because the reduced reaction wheel radius to fit inside the frame does not fit over the motor encoder. Originally, the flywheel mounted onto the motor spindle via a press fit. Redesign of this as a slip fit allowed removal of the flywheel without damage to the motor. While this increased adaptability of the prototype, it creates the possibility of a tilt between central axes of the flywheel and motor. A 3D printed mounting jig (Figure 3) aligned the reaction wheel to the motor. After mounting, a tilt angle of 0.38° degrees existed between the body and the flywheel. This tilt resulted in vibrations in the system. Future implementation of press fit mounting will result in a more balanced reaction wheel allowing for higher angular velocities. Higher angular velocities increase the ability of the reaction wheel to make corrections while adding no weight to the system. The system-mounting bracket (Figure 4) allows for press fitting of the flywheel because removing the flywheel from the motor is no longer necessary to separate the reaction wheel system from the frame.
Motor Selection:

To meet various design considerations, careful consideration of motor selection was necessary. The motor must be compact and lightweight, able to fit inside the small available space with dimensions of 10cm X 10cm X 5 cm. It needs high torque to cause strong reactions that can adequately control the attitude of the drop package. It must be precisely controllable, with fast acceleration and deceleration. Lastly, it must have relatively low power consumption and run off a modest voltage. Overall, the motor must be compact, efficient, powerful, and sensitive.

The two classes of motors under consideration are brushed and brushless DC motors. Brushed motors are simple, inexpensive, and easy to control. The commutator supplies current to
the armature via physical contact with the brushes. Permanent magnets surrounding the core interact with the armature as it charges, causing rotation. They have only two wires, and are simple to control with an H-bridge by varying the effective voltage potential across the motor via pulse width modulation. However, they often lack an accurate method to determine speed or position of the motor; this makes precise control difficult and reaction times to input relatively slow. Furthermore, while brushed motors have good torque at stall speed, torque drops off approximately linearly due to friction with the brushes. Finally, brushed motors tend to create much more electrical noise than a brushless alternative, in part because of arcing caused by the brushes.

Brushless motors effectively reverse the design of the brushed motor putting the permanent magnets on the rotor and electromagnetically charged poles around the perimeter. These poles charge at precisely the correct time and sequence for the motor to rotate. This means continuous knowledge of the rotor’s speed and position is necessary. There are two effective methods of doing this. The first is to measure the back electromagnetic field (BEMF) which is directly proportional to the motor speed. However, since there is no BEMF when stationary, there is a lag time at very low speeds preventing establishment of effective control. This project requires constant switching of direction and precise control even at low speed, thus a better alternative is to use hall sensors. These detect the magnetic field of the permanent magnets; thus, revealing the absolute position of the rotor at all times. This allows for faster reaction rates than brushed DC motors and more accurate control. Since brushless motors have no physical contact with brushes, they are more efficient, have high output torque, create less heat, and have a better torque curve over a large range of speeds. Initial prototyping stages used brushed DC motors because of their ease of control; however, the final product used brushless DC motors due to the constraints imposed on this project.

There is a wide variety of available brushless DC motors. Consumer grade brushless motors, such as those used in drones and remote controlled cars were initially an attractive option. These motors are compact and have very high torque. However, they almost exclusively measure BEMF in combination with an electronic speed controller (ESC) to operate the motor. This system does not provide the requisite resolution or response times needed for effectively controlling the reaction wheel. In fact, many of these motors will only spin one direction or require very special components that allow only limited capabilities. Thus, industrial grade brushless motors became the only reasonable option to account for these issues. While there are many companies manufacturing high quality motors, Maxon Motors, a Swiss company, stood out. They produce very high quality brushless DC motors commonly used in medical, robotics, and aerospace applications. Their motors have high energy density, and very precise control using hall sensors paired with digital encoders. Furthermore, commercial reaction wheel systems, such as the Cubli project, used Maxon motors to great effect.

Final design of this project used the Maxon EC flat series of motors. These motors have a unique, flat, low profile design that fits well within the constraints imposed by the monocoque. These motors range in power from 0.2 to 90 W. Two critical factors guide the motor sizing process. First is the amount of angular momentum that can be stored in the flywheel. This is proportional to the moment of inertia of the flywheel and the maximum speed that the flywheel may obtain. The second factor is the response time to bring the package to zero rotational speed governed by the torque of the motor. Estimates from videos of weather balloon launches suggested an initial rotation of the package about the z-axis of approximately 10 RPM. Using this speed and the moment of inertia estimated with a Solidworks model, it is possible to
calculate the initial angular momentum of the package. By the conservation of angular momentum, the angular momentum of the flywheel is equal to the momentum removed from the rotating body. Rearrangement of the equation for conservation of angular momentum leads to calculation of the maximum initial rotational speed of the body that the motor can negate with the reaction wheel. This, along with response time calculated from kinematic relationships and Newton’s second law, formed the selection criteria for the final motor. A detailed analysis of this process is in Appendix E, and resulted in the 30 W and 50 W EC-45 flat series motors as the strongest candidates.

The 30 W motor can stop the package up to an estimated initial rotation of 60 RPM, with a response time of 1.13 s. The 50 W motor has a higher nominal speed and can stop initial rotations of up to 105 RPM. It has a response time of 1.32 s to bring the package from that maximum speed down to zero, or a 0.74 s response time for an initial speed of 60 RPM. The 30 W motor is completely adequate for this system, however due to production lead times of over 10 weeks, the prototype used the higher performing 50 W motor. The 50 W motor is very similar in both size and weight to the 30 W motor; the critical difference is that it is a 24 V system instead of a 12 V system like the 30 W motor. The 50 W motor requires two batteries to operate which impacts both size and weight constraints when implemented into the final product. However, for the prototype, those constraints are not a concern, and the 50 W motor is a valid choice for testing, tuning, and implementation of the PID control system. The experimentally calculated moment of inertia of the prototype allows for a comparison between the performance of the 50 W motor on the prototype board and the expected performance of the 30 W motor on the drop package. Both motors can store more than enough angular momentum, so the response time, directly related to the angular acceleration of the body, defines performance. Appendix E details the calculation of angular acceleration given the torque of the motor and the moment of inertia of the respective body. In summary, the 50 W motor should accelerate the prototype board at 4 rad/s^2, while the 50 W motor should accelerate the monocoque at 5.5 rad/s^2. Thus, the 30 W motor implemented in the final drop package should yield equivalent or better performance compared to testing done with the 50 W motor on the prototype.

Sensor:
Throughout the drop, monocoque control and stabilization must be fully autonomous. Elimination of z-axis rotation requires measurement of package orientation and motion by some kind of sensor. An onboard microcontroller interprets inputs from the sensor, calculates required reactions, and activates the reaction wheel motors.

The sensor implemented in the final design must be accurate and robust. Research of available sensor options included: magnetometers that measure orientation, gyro sensors that measure angular velocity, and accelerometers that measure linear accelerations. These sensors use a wide variety of communication protocols. It is easy to read the outputs of analog sensors, but they are inaccurate and can have significant noise associated with their signal. Digital I2C and SPI communication protocols are more complicated from a programming viewpoint, but provide higher quality sensor data.

Remote controlled drones initially proved interesting because of their use of flight controllers. Flight controllers use a nine degree of freedom (DOF) sensor package to track orientation, velocity, and acceleration during flight. A nine DOF package consists of an accelerometer, gyroscope, and magnetometer on each of the three coordinate axes. However,
existing flight controllers work exclusively with their specific drone model, and are therefore impractical for use in this project.

This project uses a nine DOF Bosch BNO055 absolute orientation sensor, such as those that form the base of a flight controller system, to measure the orientation and angular accelerations of the package as it falls. The BNO055, which communicates digitally through I2C protocol, is an attractive sensor for several reasons. First, it has a built in miniature processor that uses all three sensor types to determine an accurate orientation in three-dimensional (3D) space. Second, it is easy to obtain the raw sensor data from any of the nine sensors, which is useful for prototyping. Finally, with a premade Adafruit® breakout board, it is easy to implement with the design microcontroller. The Bosch BNO055 provides the project with a simple and versatile sensor to provide inputs to the microcontroller.

However, there are some limitations to this sensor. The final control system implemented in this project only used angular velocity inputs from the gyro sensor. The maximum sampling rate of this sensor is 100 Hz. While this rate is appropriate for prototyping, it does inhibit the measurement of angular acceleration and tangential acceleration that the package experiences. Development of this concept, given in Appendix F, shows that the smallest measureable increment of tangential acceleration at the outer corner of the frame is \(0.035 \, \text{m/s}^2\), which exceeds the acceptable level of \(10^{-3} \, \text{m/s}^2\). The sensor resolution is also an important parameter in this development, and a more accurate gyro sensor can help achieve better control. High-quality gyro sensors can achieve \(0.01 \, \text{degrees/s}\) of signal resolution and 3000 Hz sampling rates, which could markedly improve the control system performance. It is important to mention that an accurate estimate of tangential acceleration was made using a curve fit of angular velocity. This is discussed in the Results section.

**Microcontroller:**

An Arduino Uno ATmega328P provides the base computing power in this project to interpret sensor data, calculate the necessary flywheel reactions, and send commands to the motor controller. It has I2C serial communication ports to extract data from the BNO055 sensor as well as a preexisting control system library, discussed further in the control system section. In addition, an online database contains an Arduino library for communication with the Bosch sensor. The Uno has pulse width modulation (PWM) pins to activate the motor and the necessary number of analog (6) and digital (14) pins to assist in system prototyping.

The Arduino Uno meets the design constraints imposed on the control system. The Uno weighs 25g, making it acceptable for the current mass budget. It is less than 70mm by 55mm, and easily fits within the frame space constraints. Its upper limit for input voltage is 20V with a preferred input voltage of 12V, so a single 12-14V battery can power the microcontroller. The Uno has a 16 Mhz clock speed which is comparable to many other microcontrollers and is fast enough to carry out the control system calculations. This microcontroller satisfies all design requirements except temperature. The Uno, like the majority of microcontrollers, is rated to -40° C. The Thermal Analysis section discusses a small resistive heating system with lightweight insulation to counter this.

**Battery**
An element critical to the functionality of the control system is the battery. Battery requirements are dependent on power consumption by the motors and control electronics. Selected final design motors have a maximum stall current of 10 amps, with a motor for each plane of motion. In addition to the motors, electronics associated with the reaction wheels have a combined current less than 0.1A. This reaction wheel system uses Lithium-Polymer (LiPoly) batteries because they are energy dense, cost effective, small, and lightweight. The Turnigy 1500 mA-h 3S 20C batteries selected for use are 12.3 V systems. The 50w Maxon motor needs a 24 V system, requiring two batteries. After implementation of the 30W motor, which runs on 12 V, removal of one battery will save weight and space.

**Thermal Analysis:**

Atmospheric conditions such as temperature are largely dependent on altitude. Because of this, components in the monocoque will be subject to large temperature changes as the package gains altitude. The worst-case scenario would be a summer launch when ambient temperature could start at 35°C and decrease to -55°C at altitude. Processors and most other components on the circuit boards are only rated for -40°C; therefore not suitable for the temperatures expected at altitude. Other issues that might arise from such temperature changes deal with the resistors and capacitors on the circuitry, which are temperature dependent. The delivery of voltage and current across the board will change as the temperature does. Not only could this cause problems with the readings, but some of the on-board sensors have a temperature dependent measurement error. Low temperatures could also cause problems with the chosen LiPoly battery, inhibiting chemical reactions in the battery to produce voltage. The best course of action to protect on-board electronics from temperature problems would be to contain and insulate the components together.

A thermal analysis of the frame containing the electronic systems wrapped in a 5 mm thick layer of Aerogel, a low density, aerospace grade insulation, investigated temperature issues. Because of the complex nature of the flow around the monocoque, as well as variable speeds and convective heat transfer coefficients experienced by the body, a simplified worst-case scenario model ignores heat transfer through the Kevlar body, and instead assumes the air between the body and the frame is at the atmospheric temperature. The model included the frame with a layer of aerogel insulation on all six faces, and used free convection correlations on these faces to estimate the convective heat transfer coefficients (See Appendix G). The air velocity within the Kevlar body does not depend on the speed of the package as it moves through the atmosphere, so the heat transfer between this air and the frame is purely due to free convection. The model assumed all materials contained within the Aerogel insulation are at a constant temperature of 0°C and free convection occurs between the air and the inside surface of the aerogel. Modeled using atmospheric properties at various altitudes, the heat transfer changes significantly with temperature and elevation.

The heat transfer analysis resulted in a maximum heat loss rate of 5.03 W. This occurred at the Tropopause, the division between the Troposphere and the Stratosphere, where the package will experience the lowest temperature and relative highest pressure during the ascent. The EES file “Heat Transfer” in the supporting documents contains the model used for thermal analysis to determine the heat loss rate through an insulated frame. The microcontroller and the sensor package do not require much power to function, but the electronic speed controller consumes a substantial amount and its heat loss could possibly achieve the heat rate necessary for an insulated system. If the system electronics do not provide a high enough heat rate, small
resistance heaters can provide the difference in heat rate. A simple PID controller along with small resistance heaters can effectively regulate the package temperature as the monocoque rises to the drop altitude.

Control System PID:

The microcontroller implements a proportional-integral-derivative (PID) control loop to control the reaction wheels. PID systems are an industry standard for many automated processes that require a setpoint. This control system uses a PID program from the Arduino PID library. Figure 5 shows the PID control loop for this prototype.

A PID works by calculating error from a setpoint based upon feedback from the system (plant). The PID contains three parallel calculations that operate on the original error. The first calculation is the error multiplied by a constant, $K_p$, in the “P” portion of the loop below. The second calculation is an integration of the error over time multiplied by $K_i$ in the “I” portion of the loop. The derivative of the error (the change in error over time) is multiplied by $K_d$ in the “D” portion of the loop. The PID sums all three of these calculations to create an output. Platform reactions fed back into the PID produce a new error and the PID outputs an appropriate flywheel reaction.

Each calculation of the PID performs a specific function. The proportional calculation directly adjusts for any current error, which is effective at creating immediate responses to obtain a setpoint. However, only using proportional ($K_p$) can lead to a steady state error away from the setpoint. If a steady state error exists, then the area under an error vs. time plot will steadily increase. The integral portion of the PID corrects for this steady state error. As this error accumulates, the response from the integration will increase. Finally, the derivate portion calculates the rate of change of the error. This creates quicker response times and prevents an overshoot by monitoring the approach rate to the setpoint.

For this project, it was best to use angular velocity as an input with an output of pulse width modulation (PWM) to the motor controller. A simple dynamic analysis of the package supports this design choice. A package that is not rotating does not have any tangential or centripetal acceleration, so the control loop should maintain a setpoint of zero angular velocity.

Mark I:
In order to accomplish the design objective, development and testing of the reaction wheel system took place through a series of prototypes. The first prototype was a single degree of freedom horizontal platform shown in Figure 6. This prototype consisted of a base and platform, a low-friction bearing, a motor and flywheel, and an accelerometer. With the base secure, forces upon the platform induced an angular velocity. The attached motor and flywheel applied a moment to the platform so that the platform returned to its original orientation. This first test was a proof of concept experiment; this prototype focused on interpreting sensor data and motor control.

Testing of the first prototype obtained several important results. As a proof of concept, the test was successful. The reaction wheel was able to spin the platform in either direction using the applied torque from the motor and flywheel. The reaction to inputs such as an induced motion of the platform was unsuccessful. The accelerometer inputs to the system appeared to be random and not correlated to the motion of the platform. Because of this signal noise, proper interpretation of inputs was impossible. An analog accelerometer with voltage amplifiers increased the noise in the signal. Noise in the input signal resulted from an inadequate sampling rate of the microcontroller. The main take away from this test is the need for higher precision components in the system. To this end, future prototypes featured replacements of the motor, sensors, and flywheels with better alternatives.

Mark II:

The second prototype was an improvement on the first prototype using several updated components. This prototype mounted to a horizontal square plate on top of a low-friction bearing. The main improvements of this prototype implemented the digital Bosch BNO055 sensor and a PID control loop.

The PID control system took angular orientation data from the sensor and attempted to maintain a setpoint. A PID loop calculated the magnitude of motor reactions and the orientation of the plate relative to the setpoint defined the rotational direction of the motor. This prototype failed to achieve precise control of the plate orientation due to low torque of the hobby motor and the small moment of inertia of the plastic flywheel. This prototype succeeded in establishing communication between the sensor and the microcontroller, as well as providing a preliminary, qualitative assessment of the functionality of the control system.

This prototype showed the need for a lower-friction testing platform to approximate more closely the conditions experienced in freefall. It was also clear that for the project to succeed it
needed a high quality motor. The motor needed precise control along with an appropriately sized flywheel to achieve the desired z-axis stabilization.

**Mark III:**

The third prototype carried over most of the ideas of prototype Mark II (Figures 7 and 8) but implemented a variety of new components. A Maxon brushless DC motor and machined flywheel replaced the hobby motor and plastic reaction wheel of the second prototype. Mark III redesigned the testing platform in order to emulate a free falling body more accurately. To accomplish this, Mark III hung on fishing line from a PVC frame. The thin string has a low torsional resistance. Blue-tooth communication implemented between Mark III and the computer serial monitor ensured no cables would add resistance to the prototype’s movement.
Several issues arose during initial testing of this new prototype. First, the output from the PID required mapping to a PWM signal with duty cycle between 10 – 90% such that the motor controller could properly interpret it. Second, the PID library required modification such that it could output both positive and negative values corresponding to the two directions of the motor rather than direction being dependent on the sign of the error term. This led to issues when implementing an integral component, i.e. Ki. For example, imagine the error is very near the setpoint with the body rotating at +0.01 rad/s and the motor spinning at +1000 RPM. The instant the body crosses the setpoint, it rotates at -0.01 rad/s and the PID commands the motor to spin at -1000 RPM, which is a much greater change in rotational speed than necessary. Allowing negative output from the PID loop and dictating motor direction based on the sign of that output resolved this issue.

Improvements in the code allowed for more precise testing and data collection on the Mark III prototype. Appendix H contains a flowchart of the code, while the complete Arduino file is in the supporting documents. Additionally, Figure 9 shows a complete wiring diagram of Mark III. Using three variable resistors, the user can set Ki, Kp, and Kd of the PID before turning the system on. Adjusting the values of Ki, Kp, and Kd allows for tuning the PID to optimal performance.

Activating a toggle switch turns on the PID after five seconds. Within these five seconds, the user spins the body and the PID will stop the rotation once it engages. These experiments are wireless and do not involve reprogramming of the Arduino between runs. The input to the PID was angular velocity because with zero angular velocity there is both zero tangential, and centripetal acceleration.

The Mark III testing platform has an estimated moment of inertia of 0.0213 m²·kg. Appendix I contains an experimental determination of this moment of inertia. SolidWorks™
generated a moment of inertia of the monocoque about the z-axis at 0.010 m²·kg. The moment of inertia of the prototype board is about double that of the monocoque, but the 50 W motor used on the prototype board has only 60% more torque than the 30 W motor that the drop package will use. Thus the prototype board is a good representation of the actual drop package using the 30W motor.
Testing and Results:

Testing the reaction wheel prototype revolved around two rounds of experimental trials. The first method used angular velocities as the input to the PID controller, while the second method used absolute Euler angles as the input; in both cases the setpoint was zero. The Arduino analogWrite function has an 8-bit resolution limit, so the output from the PID ranged from -255 to +255, where the sign indicates direction of the motor. This output mapped to a pulse width modulation (PWM) duty cycle between 10% - 90%. This range of duty cycles represents the acceptable limits that the motor controller can properly interpret. The motor controller then maps the PWM duty cycle to a rotational speed ranging from 0 – 5000 RPM, and commands the motor to this speed using its own, completely independent, PI controller. Acceleration of the motor is not directly controlled but held constant at the nominal value of 2500 RPM/s. Ultimately the goal of each set of trials was to tune the coefficients of the PID loop to achieve maximum performance. The tuning procedure involved sequential progressions of Kp, Ki, and Kd and selection of the combination that lead to optimal results. Steady state error compared to the setpoint, the response time necessary to achieve steady state, and ability to maintain acceleration of the package under the goal of 0.1% g defines loop performance.

In the first round of trials angular velocity was the input; this is representative of expected initial conditions immediately after the drop package detaches from the balloon. Videos from the atmospheric science department indicate rotation about the z-axis of the package of around 10 RPM. Reducing this rotational speed to zero as quickly as possible is critical to bringing acceleration within acceptable limits. In order to ensure performance on the final product, trials on the prototype board ran at an initial speed of about 20 RPM. Using the relationships derived for motor selection involving conservation of angular momentum, this is roughly equivalent to the 30 W motor on the drop package spinning at 24 RPM, which is well above the expected initial conditions.

Figure 10 shows the progression of increasing values of Kp, with Ki and Kd held at zero. Increasing values of Kp resulted in increasing reduction of rotational speed. For example, with Kp of 20 the speed the speed of the body is reduced by 7 RPM, and with Kp of 50 it is reduced by a full 10 RPM. However, there is a point at which the response becomes increasingly unstable. There is not enough dampening to control the proportional response, resulting in high frequency oscillation at steady state that increases in amplitude for Kp greater than 45. In every trial, there is a significant steady state error, which is indicative of purely proportional responses and requires an integral component to rectify. The best performance without steady state oscillation is achieved for values of Kp between 35 and 45.
Figures 11 shows the progression of increasing Ki, at Kp of 35 and Kd of zero. Many additional, full sized supporting plots are in Appendix J. There is a variety of interesting trends exhibited by the implementation of an integral response. First, in every case the steady state error eventually goes to zero. The time this takes to happen is inversely proportional to Ki. At Ki equal to 500 it takes well over 15 seconds for the error to reach zero, which is unacceptable as this is three quarters of the entire flight time. At Ki equal to 1800, on the other hand, it takes a mere 2 seconds to reach zero error. Second, the response has two distinct components. There is the proportional response defined by a steep linear decrease in rotational speed, followed by the integral response, defined by a slower exponential decay towards zero. For small values of Ki the integral response is dominant, resulting in the long response times. As Ki increases, error accumulates more quickly, becoming significant even during the immediate response usually governed by the purely proportional component. The effect is that the linear response increases with increasing Ki, up to a certain limit. For values greater than or equal to 2000, the response overshoots the setpoint, resulting in longer response times. Ki equal to about 1800 is the critical point that maximizes the linear response without overshooting the setpoint. This results in the shortest response time, and zero steady state error. Lastly, at Ki of 2500 there is a strange, sharp spike at about 3.5 seconds due to a limitation of the motor controller covered in detail in the section on limitations.
Introduction of Kd seems to have little positive effect, leading to undesirable behavior especially at steady state. Figure 12 shows the progression of Kd for Ki at 1800 and Kp values of 40, 50, and 55. Even for a value as small as 0.05, high frequency oscillation is introduced that increases in amplitude proportionally with increasing Kd. Large values of Kd, such as 1, dampen the response resulting in an exponential decay rather than a linear one. This is potentially useful for damping an unstable proportional response, such as values of Kp greater than 45, which could lead to better performance. However, the high frequency oscillation remains, and ruins any benefit achieved through a derivative response. The output of the PID leads to a torque from the motor, and this torque accelerates the prototype board. However, angular velocity, not angular acceleration, is the input to the control loop. An integration separates these variables, which introduces a phase angle and response lag. This response lag may explain the high frequency oscillation. Centripetal acceleration is dependent on the instantaneous angular velocity; even with zero angular acceleration, rotating at a constant speed yields centripetal acceleration. Thus angular acceleration is not an acceptable input to the PID and the implicit integration between the output and input is unavoidable. The derivative term often proves difficult to implement in many engineering applications and is commonly left out in favor of a purely PI controller. Tuning the PID coefficients yielded the best performance at values of Kp between 35 and 45, Ki of 1800 - 1900, and Kd of 0.
Figure 13 shows two trials ran over a longer period of time, with the PID tuned to optimal parameters and energy added to the system by physically spinning the prototype board. Large spikes in the plot represent the user spinning the board. The reaction wheel consistently responds accordingly, and brings the board to nearly zero rotational speed after every disturbance. This proves its operational potential during an actual drop where environmental perturbations continuously add and remove energy from the system. The reaction wheel can respond to this by transferring rotational energy between the body and the flywheel.
The second round of trials involved using the Euler angle in the plane perpendicular to the z-axis as the input to the PID control loop instead of angular velocity. For these trials, the PID attempted to maintain a set angular position. The objectives of this project require vector sums of tangential and centripetal acceleration under the prescribed limit of 0.1% g. Simply maintaining zero angular velocity meets this criteria, while maintaining a specific orientation in space exceeds this scope. However, the Euler angles from the sensor had smoother, higher resolution output than angular velocity. The sensor reports Euler angles with a resolution of 0.00017 rad (0.01 deg), while angular velocity have a resolution of 0.01 rad/s. Furthermore, even with the system at rest, readings from the gyroscope reported noisy data compared to the Euler angle. This noise made a tolerance level of 0.02 rad/s, with values less than this set to zero, necessary for successful operation when using angular velocity. These findings provided the justification for testing the system with Euler angles and maintaining a fixed orientation.

Trials using the Euler angle began with the system at rest aligned with its setpoint. Next, the code introduced a 10 degree shift from the setpoint. Figure 14 is the progression of Kp with zero integral or derivative components. Increasing Kp reduces the response time, just as seen with angular velocity. Values of Kp greater than six lead to an under-damped response that overshoots the setpoint and then undergoes oscillation. A key difference when comparing these trials to those using angular velocity is that the relative steady state error of the purely proportional response is much smaller. This is a potentially attractive attribute and provides strong motivation for implementation. However, 10 degrees from the setpoint is relatively small and behavior for large errors could be very different. Adding both the integral and derivative
components resulted in no behavior different from that already seen when using the gyroscope; this includes the high frequency oscillation caused by Kd (Appendix J).

Immediately after cut away from the balloon, the drop package will be spinning at approximately 10 RPM. Using angular velocity as input to the PID controller is therefore the most reasonable option for correcting this initial condition and bringing the rotational speed to zero. After reaching steady state, perturbations during the drop will most likely resemble small step inputs, and it may be preferable to switch and use Euler angles as the input. The smaller steady state error and the higher resolution, smoother output from the sensor could lead to better performance during the actual drop period. Data recorded in the first few test drops will determine if this is a good route to take.

Verification of microgravity must account for contributions from both centripetal and tangential accelerations. An analysis conducted on prototype Mark II, in the best-case scenario with Kp = 35, Ki = 1900, Kd = 0, to see if microgravity was under $10^{-3}$ g produced the results seen below in Figure 15. Centripetal acceleration is a function of radius, which is constant, and angular velocity, which is shown on the graph. A centripetal acceleration of $10^{-3}$ g and the radius of a CubeSat (0.0707 m) limit angular velocity to 0.119 rad/s in order to achieve quality microgravity. The slope of the angular velocity’s decay towards zero, which is equivalent to the angular acceleration, quantifies tangential acceleration. Multiplying this slope by the radius of a CubeSat yields the average tangential acceleration which, when normalized by gravity, equaled $2.43 \times 10^{-4}$ g. The magnitude of the vector sum of average tangential acceleration and centripetal
acceleration falls under $1.03 \times 10^{-3} \, \text{g}$ within $985 \, \text{ms}$ of arming the reaction wheel system. Furthermore, after 3.1 seconds, the sensor recorded no movement, and thus no acceleration could be detected, leading to an acceleration magnitude of zero.

**Limitations:**

A number of issues arose throughout the design process related to both the control system and various limitations of the experimental procedure and components. The motor controller was one of the more evident shortcomings. The ESCON 24/2 motor controller can output up to 2 A of continuous current or a peak of 4 A for less than 2 s. Reaching these limits produces strange spikes in the angular velocity as illustrated in Figures 11 and parts of Figure 13. To investigate this behavior, Figure 16 depicts a trial, ran with a large initial rotational speed to immediately saturate the system, plotted alongside actual current demand as reported by the motor controller. The right side of Figure 16 is the output from the PID, and depicts that the instant the system is armed the output corresponds to the maximum speed of the motor and remains at this value the entirety of the trial. As the motor accelerates towards the demanded speed, the required current increases until it approaches the 4 A limit of the motor controller. At this point, the current rapidly reverses direction and outputs $-4 \, \text{A}$. Immediately after reaching this negative limit, the current reverses direction again and briefly reaches $+4 \, \text{A}$. A full explanation of this response is unknown, however it clearly relates to behavior of the motor controller taken to ensure that the system performs within allowed parameters. Programming the motor controller with less aggressive values of acceleration yields proportionally lower current draw, avoiding the issue. However, lowering the value of acceleration increases the response time. The critical value of acceleration that minimizes response time, while staying within the limits of the motor controller, falls between 1500 – 2000 RPM/s depending on the initial conditions. Another
alternative is to use a different motor controller with higher allowable current limits. For example, the ESCON 50/5 motor controller can output 5 A continuously or up to 15 A for less than 20 s (See Appendix E).

An inherent limitation of the system is the amount of angular momentum that may be removed from the package or prototype and stored in the flywheel. This is limited by the moment of inertia of the flywheel and the maximum speed of the motor. If the angular momentum of the body is greater than that which may be stored in the flywheel, then the system becomes saturated. Calculations performed earlier for motor sizing, see Appendix E, estimated that the 50 W motor on the prototype board (max speed of 5000 RPM) can store the amount of momentum corresponding to the body spinning at up to 48 RPM. Actual trials, such as shown in Figure 16 confirm this value. The speed of the prototype is initially at 61 RPM and eventually is reduced to 15 RPM, a reduction of 46 RPM. At that point the motor is at maximum speed and the system is saturated. This is within 5% of the expected value and confirms that estimated values for the moment of inertia of both the flywheel and prototype board are accurate. This experimental verification lends confidence to the predictions made for the 30 W motor implemented on the final product. System saturation is unlikely as the flywheel should be able to store the amount of momentum corresponding to the drop package spinning at 60 RPM.

The BNO055 sensor exhibited certain limitations. Euler angles and angular velocities retrieved from the sensor had smooth output with very little noise, but the accelerometer used to check the quality of microgravity proved more problematic. For the trial with Kp at 35, Ki at 1800, and angular velocity used as the PID input,
Figure 17 shows the output from the accelerometer along two perpendicular axes in the plane normal to the axis of rotation. When the angular velocity reaches zero, the linear acceleration oscillates with an amplitude of approximately 0.5 m/s², which is well beyond the required limit of 10⁻³ g. This signal noise could be a result of vibration from the motor, or out of plane swaying of the platform. Dividing the change in angular velocity between two loops of the PID by the time it took to run the loop indirectly measured the angular acceleration. Figure 18 is the resulting angular acceleration for the aforementioned trial and clearly indicates significant oscillations with amplitude over 1 rad/s². These oscillations are believed to be in part due to the resolution of the sensor. The sensor reports angular velocity to the hundredth of a rad/s, while typical loop speed was about 18 ms. This results in resolution of angular acceleration of 0.56 rad/s², which is beyond acceptable limits. Stabilization of the prototype platform, to isolate rotation in a single plane, would help reduce these spurious accelerations. Upgrading the sensor to a model with higher signal to noise ratio, faster sampling rate, and higher resolution could also remove this concern.
In some ways, the current system is different than many common applications for a PID. Most applications involve a damped system, for example maintaining temperature in a building, or speed in a car. Turning off the furnace causes the temperature inside the building drops as heat is lost to the surrounding environment. Releasing the throttle allows air resistance and friction to slow the car. Furthermore, in most applications reducing the output does not directly affect the state of the system. Releasing the throttle in a vehicle is not the same as applying the brakes. On the prototype board, however, a smaller output correlates to a lower speed, resulting in the motor decelerating. This deceleration results in a torque that opposes movement of the body towards the setpoint. This is equivalent to hitting the brakes, and the car accelerating away from the desired velocity. The limitation of the PID is that it must use one input and the reaction wheel system needs to control both tangential and centripetal accelerations. Centripetal acceleration is a function of angular velocity, while tangential acceleration is a function of angular acceleration. Limiting both of these parameters with the same input and a single setpoint is the downside to a PID control loop.

**Project Future:**

As the project moves forward, incoming groups will need to address several areas. These groups may identify additional areas of concern, however, at this point, the following areas will need investigation as the reaction wheel system progresses.

Angular rotation occurs commonly in weather balloon launches. To maintain a sellable quality of microgravity, the z-axis flywheel must counteract angular rotation. Future drop testing of a monocoque without a reaction wheel system will determine whether the x-axis and y-axis reaction wheels are necessary. The initial package experiments will serve as a control group with which to compare reaction wheel performance. It is possible that the reaction wheel system would be able to eliminate the need for a boom and tail fin. Wind tunnel tests or initial
monocoque test drops will quantify restoring moments from the tail. If reactions wheels are comparable to the restoring torques from the fins, future groups could remove fins which would save substantial weight in the package.

It is beneficial to implement the Maxon 30W motor on the monocoque instead of the 50W motor used in the prototype. The 30W motor is 35g lighter and is a 12-volt system. As stated previously, the 30W motor will perform adequately in the package. The change to a 12-volt system also eliminates one battery pack weighing 148 grams. This change will not cause any changes in mounting brackets or motor control electronics.

The thermal analysis section shows that internal temperature of the monocoque may need to be regulated. After final assembly of all onboard electronics is complete, an evaluation of the heat generation from the electronics will determine whether a resistive heating is necessary to maintain a suitable temperature.

Finally, implementation of a press fit instead of a slip fit on the flywheel will minimize vibrations. Additionally, dynamic balancing will minimize vibrations caused by an unbalanced wheel rotating at high RPMs. A high precision balancing company, Dynamic Laser Solutions, would be the optimal choice for this because of their history in the field.
### Appendix A

#### Mass Budget

<table>
<thead>
<tr>
<th>Component</th>
<th>Lb</th>
<th>Kg</th>
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<tbody>
<tr>
<td>Reaction Wheel</td>
<td>0.28</td>
<td>0.125</td>
</tr>
<tr>
<td>50 W Motor</td>
<td>0.24</td>
<td>0.110</td>
</tr>
<tr>
<td>Motor Controller (MC)</td>
<td>0.02</td>
<td>0.007</td>
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<tr>
<td>Microcontroller</td>
<td>0.06</td>
<td>0.025</td>
</tr>
<tr>
<td>Sensor</td>
<td>0.01</td>
<td>0.003</td>
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<tr>
<td>Wiring</td>
<td>0.07</td>
<td>0.030</td>
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<tr>
<td>MC Motherboard</td>
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<td>0.082</td>
</tr>
<tr>
<td>Battery</td>
<td>0.47</td>
<td>0.213</td>
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<tr>
<td><strong>Total</strong></td>
<td>1.31</td>
<td>0.595</td>
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# Appendix B

## Failure Modes Effect Analysis

<table>
<thead>
<tr>
<th>Failure</th>
<th>Significance</th>
<th>Effect</th>
<th>Likelihood</th>
<th>Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronic malfunction due to temperature</td>
<td>No control active control system in drop package</td>
<td>Possible loss of acceptable Microgravity</td>
<td>Medium</td>
<td>Add resistive heating and insulation</td>
</tr>
<tr>
<td>Flywheel Separation</td>
<td>No corrective torque</td>
<td>Possible loss of acceptable Microgravity</td>
<td>Low</td>
<td>Change from slip fit to press fit</td>
</tr>
</tbody>
</table>
# Appendix C
## Expense Report

### Microgravity Controls Team Expense Report

<table>
<thead>
<tr>
<th>Company</th>
<th>Part Number</th>
<th>Description</th>
<th>Quantity</th>
<th>Cost</th>
<th>Shipping</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Turnigy</td>
<td>1500mAh 3s 20c Lipo Pack</td>
<td>Batteries</td>
<td>2</td>
<td>$24.06</td>
<td>$4.78</td>
<td>$28.84</td>
</tr>
<tr>
<td>Turnigy</td>
<td>E3 Compact 2S/3S Lipo Charger 100-240v (US plug)</td>
<td>Charger</td>
<td>1</td>
<td>$17.99</td>
<td>$0.00</td>
<td>$17.99</td>
</tr>
<tr>
<td>Littelfuse</td>
<td>576-0157004.DR</td>
<td>4 amp fuse</td>
<td>1</td>
<td>$2.43</td>
<td>$7.99</td>
<td>$10.42</td>
</tr>
<tr>
<td>McMaster-Carr</td>
<td>8960K14</td>
<td>Steel for flywheel fabrication</td>
<td>1</td>
<td>$43.34</td>
<td>$0.00</td>
<td>$43.34</td>
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<tr>
<td>Maxon</td>
<td>469253</td>
<td>Motor</td>
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<td>$249.20</td>
<td>$0.00</td>
<td>$249.20</td>
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<tr>
<td>Maxon</td>
<td>466023</td>
<td>Motor controller</td>
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<td>Connector Cable</td>
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<td>Maxon</td>
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<tr>
<td>Adafruit</td>
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<td>Sensor Breakout Board</td>
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<td>$34.95</td>
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<td>Ace Hardware</td>
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<td>Test Platform Supplies</td>
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<td>$25.78</td>
<td>$0.00</td>
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<tr>
<td>UW Machine Shop</td>
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<td>Flywheel Fabrication</td>
<td>1</td>
<td>$350</td>
<td>$0.00</td>
<td>$350</td>
</tr>
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</table>

| Total         |            |                                                  |          |        |          | $1067   |
Appendix D

Flywheels

Flywheel Design

Component: Z-Axis Reaction Wheel

<table>
<thead>
<tr>
<th>Group: Senior Design Microgravit-Controlls</th>
</tr>
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<tbody>
<tr>
<td>Drawing Created: Cornell B 2/13/17</td>
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<tr>
<td>Units: Millimeters</td>
</tr>
<tr>
<td>Tolerances:</td>
</tr>
<tr>
<td>Material: ANSI 4140 Steel</td>
</tr>
<tr>
<td>Scale 1:1</td>
</tr>
<tr>
<td>Quantity: 1</td>
</tr>
<tr>
<td>Weight: 123g</td>
</tr>
<tr>
<td>Finish: None</td>
</tr>
</tbody>
</table>

Contact: Gideon Baldwin (307) 941-0803 or gbaldwi1@uwyo.edu

Measure motor shaft diameter prior to machining

Mill down by 0.015"
Creating a Flywheel in Abaqus

Procedure to create a basic reaction wheel and analyze it for torque resistance. This reaction wheel is a linear elastic model with 3D incompatible mode elements to counteract shear locking. The mesh is a sweep type.

1) Open `Z-axis_Reaction_wheel.py` in Notepad++
2) You can change the parameter of the wheel to match a new design (lines 24 through 37)
   a. The rest of this script is Abaqus Commands **DO NOT ALTER**

   ```python
   # Parameters ALL DIMENSIONS IN MM. STRESSES ARE IN MPa
   Rout=90/2 # Outer Rim Diameter
   Rin=82.4/2 # Inner Rim Diameter
   ThkSpoke=2/2 # Total Spoke Thickness
   RSpindle=5 # Outer radius of the inner spindle
   RMHole=2/2 # Diameter of Spindle
   FilletOuter=2 # Fillets of spokes to outer ring
   FilletInner=2 # Fillets of spokes to inner spindle
   ThicknessA=5 # Thickness of spokes and spindles
   ThicknessB=12.7-ThicknessA # Thickness of outer ring to keep entire thickness to 0.5"
   MeshSize=3 # Mesh resolution
   Torque=100 # Torque applied to inner spindles
   Material Properties 1012 Steel
   El=2000000.0 #
   Poss=0.29 #
   ```

3) Open Abaqus
   a. Abaqus will open 2 windows: a terminal (black) window displaying license numbers and the Abaqus window.
4) Go to File  Run Script  Find and run `Z-axis_Reaction_wheel.py`
   a. The script will error out with the error message

   ![Error message](image)

   b. Dismiss the error
5) Select the interactions window (red arrow)
6) Select “Create Constraint” (orange arrow)
7) Select coupling (green arrow) and press continue
8) Click on the RP-1 node for “Select the constraint controls point” and click done (orange then yellow arrow)

9) Click Surface which was in the same region on the screen as the yellow arrow
10) Select the spindle hole (green arrow) and click done
11) Click ok in the “Edit Constraint-1” dialog box
12) Change to the load menu (red arrow)
13) Click on Create Load (yellow arrow)
14) Select moment and click continue (orange arrow)
15) Select RP-1 and click done
16) In the Edit Load dialog box, for CM3 enter the desired torque in Nmm (1Nm=1000Nmm)
17) Click ok in Edit load box
18) Click on create boundary conditions (black arrow in previous figure)
19) Select Symmetry/Antisymmetry/Encastre and click continue
20) Hold shift and click the two surfaces (green arrows) and select done
21) Select ZASYMM (U1=U2=UR3=0) and click ok
   a. This will pin the outer rim of the wheel in the x and y Cartesian directions and z rotational directions
22) Right click on Jobs (yellow arrow)
23) Click create
24) Click continue
25) Click ok
26) Click on the “+” box next to Jobs(1) and right click on Job-1 and click submit
   a. Abaqus is now running the simulation. This process will take approximately 1 minute.
27) Once the job has been completed, right click on Job-1 and click results
28) Once the job has finished running, click “Plot Contours on Deformed Shape” (black arrow)
   a. Note: The program elongates the deformations by ~1000
   b. To have an undeformed shape, repeat step 28 only click and hold on “Plot Contours on Deformed Shape” until plotting options show up
29) To rerun a configuration, select File→New Model Database→With Standard/Explicit Model
30) Select NO to Save changes made to the unnamed model database
31) Restart at Step 1
Appendix E

Motor Selection

Dynamic Relationships: Impulse Momentum and Conservation of Angular Momentum

\( I_p \) (Moment of Inertia of Package about axis normal to earth)

\( I_w \) (Moment of Inertia of flywheel about axis normal to wheel)

\( \omega_{1p} \) (Initial angular velocity of package)

\( \omega_{2p} \) (Final angular velocity of package)

\( \omega_{1w} \) (Initial angular velocity of fly wheel)

\( \omega_{2w} \) (Final angular velocity of fly wheel)

\( \alpha_w \) (angular acceleration of fly wheel)

\( M \) (Instantaneous torque of motor)

\( \bar{M} \) (Average (nominal) torque of motor)

\( \Delta t \) (Time for package to decelerate from initial to final angular velocities)

Impulse momentum is described by

\[
(1) \quad I_p \omega_{1p} + \int_{t_1}^{t_2} M \, dt = I_p \omega_{2p}
\]

Assumption: \( M \approx \text{constant at nominal torque value taken from data sheet} \)

\[
(2) \quad I_p \omega_{1p} + \bar{M} \Delta t = I_p \omega_{2p}
\]

The torque from the motor is proportional to the inertia and angular acceleration of the flywheel

\[
(3) \quad \bar{M} = I_w \alpha_w
\]

Substituting equation (3) into (2)

\[
(4) \quad I_p \omega_{1p} + I_w \alpha_w \Delta t = I_p \omega_{2p}
\]

From kinematics

\[
(5) \quad \omega_{2w} - \omega_{1w} = \alpha_w \Delta t
\]

Substituting (5) into (4) and rearranging

\[
(6) \quad I_p \omega_{1p} - I_w \omega_{1w} = I_p \omega_{2p} - I_w \omega_{2w}
\]

Note that \( \alpha_w \) is a negative value, if we define it as positive and flip the positive signs to negative, (6) may be rewritten as
Notice that equation (7) is the conservation of angular momentum, as expected. Initially the wheel is at rest and the package is rotating. The desired end state is that the package is at rest with the flywheel spinning. Thus

\[ \omega_1w = 0 \text{ and } \omega_2p = 0 \]

This reduces equation (7) to

\[ (8) \quad I_p \omega_1p = I_w \omega_2w \]

Equation (8) says that the amount of angular momentum that can be removed from the package is equivalent to the amount of angular momentum that may be stored in the flywheel. \( I_w \) and \( I_p \) are known values and \( \omega_2w \) can be taken as the nominal speed of the motor as provided by the data sheet. Thus solving for \( \omega_1p \) in equation (8) yields.

\[ (9) \quad \omega_1p = \frac{I_w}{I_p} \omega_2w \]

Equation (9) solves for the maximum initial speed of the package that the reaction wheel and respective motor can bring to zero. This relationship, as well as response time, served as the basis for the motor sizing and selection process see Motor Evaluation Excel spreadsheet in supporting documents.

**Response Time**

\( \alpha \) (Angular acceleration of package)

\( \omega_i \) (Initial angular velocity of package)

\( \omega_f \) (Final angular velocity of package)

\( \Delta t \) (Time for package to decelerate from initial to final angular velocities)

\( T \) (Motor torque)

\( I \) (Rotational moment of inertia of package)

With constant angular acceleration, note \( \alpha \) is taken as a purely positive constant

\[ (1) \quad \omega_f = \omega_i - \alpha \Delta t \]

Specifying \( \omega_f = 0 \)

\[ (2) \quad \Delta t = \frac{\omega_i}{\alpha} \]
Now, from the rotational analog of Newton’s Second law,

\[ (3) \quad T = I\alpha \]

Rearranging

\[ (4) \quad \alpha = \frac{T}{I} \]

Substituting (4) into (2) yields the estimated response time

\[ (5) \quad \Delta t = \frac{\omega I}{T} \]

Equation (5) is used in the motor sizing and selection process; see Motor Evaluation Excel spreadsheet in Supporting Documents.

**Comparison of 30W and 50W motors**

\[ I_p = 0.010 \text{ kg} \cdot \text{m}^2 \text{ (moment of inertia of package about z axis, estimated using Solidworks model)} \]
\[ I_b = 0.021 \text{ kg} \cdot \text{m}^2 \text{ (moment of inertia of prototype board about z axis, estimated using experimental method)} \]
\[ T_{30} = 55.0 \text{ mN} \cdot \text{m (torque of 30W motor)} \]
\[ T_{50} = 83.4 \text{ mN} \cdot \text{m (torque of 50W motor)} \]

The rotational analog of Newton’s Second law is

\[ (1) \quad T = I\alpha \]

Solving for acceleration

\[ (2) \quad \alpha = \frac{T}{I} \]

Solving for the angular acceleration of the drop package with the 30 W motor

\[ \alpha_{30} = \frac{T_{30}}{I_p} = \frac{0.055 \text{ N} \cdot \text{m}}{0.010 \text{ kg} \cdot \text{m}^2} = 5.5 \text{ rad/s}^2 \]

Solving for the angular acceleration of the prototype board with the 50 W motor

\[ \alpha_{50} = \frac{T_{50}}{I_b} = \frac{0.0834 \text{ N} \cdot \text{m}}{0.021 \text{ kg} \cdot \text{m}^2} = 4.0 \text{ rad/s}^2 \]

Thus the 30 W motor when implemented on the final package should have greater performance than the 50 W motor on the prototype board.
Appendix F

Sensor Resolution

The gyroscope cannot measure angular acceleration directly, so the following equation calculates the angular acceleration:

\[ \dot{\omega} = \frac{\Delta \omega}{\Delta t} = \frac{0.01 \text{ rad}}{0.02 \text{ s}} = 0.5 \text{ rad/s} \]

The tangential acceleration is calculated from the following:

\[ a_t = \omega r = 0.5 \text{ rad/s} \times (0.0707 \text{ m}) = 0.035 \text{ m/s}^2 \]
Appendix G

Heat Transfer Model

Where heat transfer calculations used thermal resistances:

The model assumed a value of -60º C for $T_{\infty 1}$ as the exterior temperature and 0º C for $T_{\infty 2}$ in the interior of the insulated frame.

Thermal Resistance due to conduction through the Aerogel insulation was the same on all surfaces and given by:

$$R_{wall} = \frac{L}{kA}$$

Where L = insulation thickness, $k$ = thermal conductivity of Aerogel, and $A$ = the area of the wall section.

Thermal resistances due to convection are given by:

$$R_{conv} = \frac{1}{hA}$$

Where $h$ is a convection coefficient dependent on the Nusselt Number:
\[ h = \frac{N u \ k}{A} \]

The Nusselt Number is dependent on geometry and different for the top, bottom, and side surfaces. Chapter 9 of *The Fundamentals of Heat and Mass Transfer* gives the relations recommended by Churchill and Chu for Nusselt Numbers on a flat plate.

For the outer surfaces:

Convection 1 corresponds to vertical plate free convection.

Convection 2 corresponds to upper surface of hot plate free convection.

Convection 3 corresponds to lower surface of hot plate free convection.
Appendix I

Moment of Inertia

Experimental Determination of the Moment of Inertia of Mark III

For experimental data see Inertia_Data_Processed.xlsx in supporting document

\[ J = I_{zz} \text{(Moment of Inertia of Package about axis normal to earth [kgm]}^2\text{]} \]

\[ T \text{ (period of unforced response of Mark III [sec])} \]

\[ a \text{ (radius of hanning supports to center of rotation [m])} \]

\[ m \text{ (mass of Mark III [kg])} \]

\[ (\text{gravity } \frac{m}{s^2}) \]

\[ h \text{ (height of hanning string [m])} \]

\[ J = \left( \frac{T}{2\pi} \right)^2 \frac{a^2 mg}{h} = 2.13 \times 10^{-3} \text{ kgm}^2 \]

Figure 22G: Experimental Determination of Moment of Inertia from System Dynamics 4th Edition by Katsuhiko Ogata, page 82-83
Modeling Moment of Inertia of Monocoque as a Cylinder

\[ I_{xx} = I_{yy} \quad (\text{Moment of Inertia of Package about axes parallel to earth}) \]

\[ I_{zz} \quad (\text{Moment of Inertia of Package about axis normal to earth}) \]

\[ m = 2.72 \, \text{kg} \quad (\text{Total mass of drop package}) \]

\[ r = 0.071 \, \text{m} \quad (\text{Radius of CubeSat}) \]

\[ h = 0.3 \, \text{m} \quad (\text{height of drop package along z-axis}) \]

Moments of Inertia are given by the following

\[ I_{xx} = I_{yy} = \frac{1}{12} m (3r^2 + h^2) = 0.0221 \, [kg \cdot m^2] \]

\[ I_{zz} = \frac{1}{2} m r^2 = 0.0034 \, [kg \cdot m^2] \]
Appendix J:

Additional Testing Data

Angular Velocity as Input
Angular Velocity as Input
Angular Velocity as Input
Angular Velocity as Input
Angular Velocity as Input
Angular Velocity as Input
Euler Angle as Input
Euler Angle as Input
Euler Angle as Input
Euler Angle as Input
Euler Angle as Input