Badger Ballistics

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1.0 FLIGHT PERFORMANCE COMPARISON SHEET

The flight comparison sheet gives a summary of the Badger Ballistic's "Lucky Bucky" rocket performance during the Midwest Rocket Launch Competition. Additional comments are given in figure descriptions.

Table 1 Flight #1 configuration and key performance values

Flight # 1			
	Actual	Theoretical	Error [%]
Mass [lb]	14.3	-	-
Motor	AeroTech J570	-	-
Max Altitude [ft]	2530	2938	16.12
Max Velocity [mph]	285.66	298.73	4.58
Max Acceleration [g's]	13.5*	18.2	34.8
Ground Hit Velocity [ft/s]	25.0	19.4	22.4

*Note: maximum output of the accelerometer, could not measure accelerations exceeding 13.5 g's

Table 2 Flight #2 configuration and key performance values

Flight # 2			
	Actual	Theoretical	Error [%]
Mass [lb]	14.3	-	-
Motor	AeroTech J570	-	-
Max Altitude [ft]	2522	2938	16.48
Max Velocity [mph]	270.2	298.73	10.55
Max Acceleration [g's]	13.5*	18.2	34.8
Ground Hit Velocity [ft/s]	24.2	19.4	19.8

*Note: maximum output of the accelerometer, could not measure accelerations exceeding 13.5 g's

Figure 1. The rocket is rolling counter-clockwise. The blue LED corresponds to deflection of control surface that applies a counter-clockwise torque to rocket (can be visually seen by looking closely at fin/control surface).

Figure 2. The rocket is rolling clockwise. The green LED corresponds to control surface deflection that applies clockwise torque to rocket.

Figure 3. The red LED corresponds to small adjustments in control surfaces to hold rocket steady, note that the control surfaces appear flush with fin.

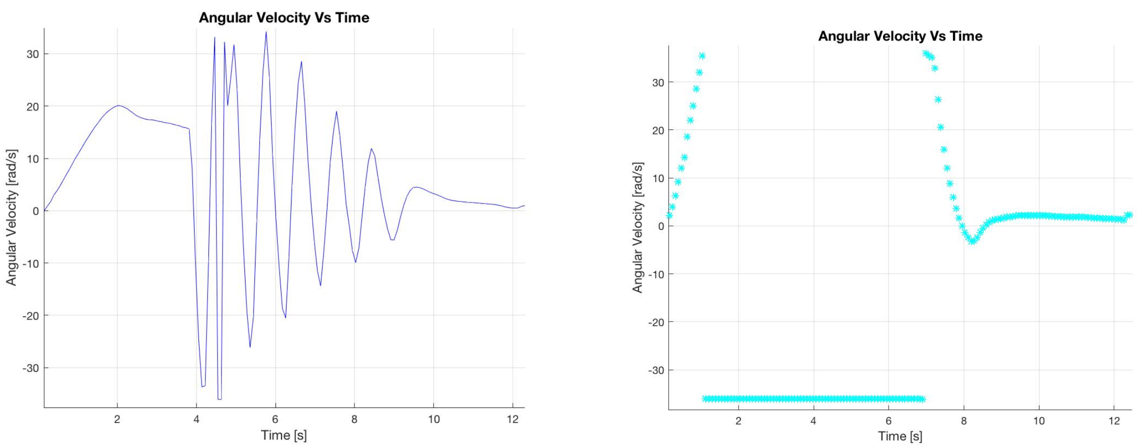


Figure 4. Angular Velocity Vs time; Left: Flight 1: The large oscillations in roll rate eventually converge to zero. Right: Flight 2: The large roll rate exceeds limits of gyroscope, creating erroneous data from 1.5 to 6 seconds. The system quickly nulls roll and holds North.

Links to videos:
Flight 1: https://youtu.be/o7wd2uwsi4Q
Flight 2: https://youtu.be/cwjTEdIajFY

2.0 Rocket Operation Assessment

The Badger Ballistics MRL Competition rocket flew two times on Sunday May 20th, 2018, and was recovered in near perfection. The first launch felt roughly 14 g's of acceleration and reached an altitude of 2530 ft. The dual deploy parachute system deployed as expected and lead to a ground hit velocity of 25 ft/s. The second competition launch left the ground with a boost of 14 g's to reach a final altitude of 2522 ft. The resulting descent velocity of was 24.2 ft/s. Both launches resulted in nominal ascents (although lower than predicted apogees), and successful descents, although slightly larger than predicted descent velocities. Overall, the operation of the Badger Ballistics 'Lucky Bucky' scratch built rocket pleased our team. We look forward to utilizing the lessons learned from this competition in pursuit of future improved high-power rocket flights.

2.1 Flight 1 - Null Roll Challenge

The first portion of the MRL competition challenge revolved around nulling the roll of the rocket during post-motor burnout flight (coast phase). The Badger Ballistics team chose to approach this challenge through control surfaces which are governed by a microcontroller PID function. For the challenge of nulling roll, our team chose to simplify the PID loops by utilizing angular velocity data rather than orientational heading (which was necessary for the second half of the challenge). This allowed for a very simple PID loop where angular velocity data from the IMU was fed into the PID function, then the output would correlate to a control surface deflection until angular velocity reached the set point of zero. The rocket would then hold this orientation by keeping the control surfaces approximately flush with the fins, with minor adjustments. If a perturbation caused the rocket to start rolling again the system would immediately implement corrective action and therefore keep the rocket within a tight window of angular movement.

2.1.1 Flight Anomalies: Flight 1

During the ascent phase of Launch 1, the downward facing video exhibits a much higher than expected tendency to roll. The rocket's angular velocity peaked at around 1600 degrees/second before the roll control phase was activated. This impacted the efficiency of the null roll algorithm's response time, but proved non-detrimental to the control system's success. Our team believes this anomaly may be resultant of a subtle fin misalignment which would induce moments about the axial direction of the rocket. In the future, this could be improved using a proper fin alignment jig during the construction phase.

During the roll control phase of Launch 1, the downward facing video footage shows a very vigorous PID response during the first moments of the control system implementation. This lead to aggressive overshooting of the rocket's roll rate for the first few loops of the PID algorithm. Once again, this did not cause a failure of the control system, but it did lead to decreased efficiency and a slightly longer roll nullification time. It also resulted in a lower apogee than predicted due to increased drag. It was determined that this anomaly was a result of too large of a proportionality constant in the null roll algorithm. This was likely too large since we tuned our roll control system in a 35-mph wind tunnel, and in flight the rocket reached nearly 10 times that velocity. After the first flight our team ran new calculations and modified these values for the second flight, which proved to achieve a much smoother roll control response.

Finally, the post-flight inspection revealed a broken fin fillet on one of the fins. This was likely caused by two factors; a lower parachute coefficient of drag causing a faster than predicted descent velocity, and poor construction techniques. During the construction phase of the rocket, the rocket fell off a stand with a large amount of force being applied to the rocket, this broke one of the fin fillets, which was repaired. However, the same fin fillet broke on landing, so it is expected the repair was not sufficient, furthermore this is likely what induced a larger than expected roll rate on ascent, since the fin could not be perfectly aligned during the repair.

The broken fin fillet was repaired in the field by injecting 5-minute epoxy into the lower airframe, then apply copious amounts of epoxy around the joint for a crude fin fillet for the 2nd and final flight.

2.1.2 Propulsion System Assessment: Flight 1

The AeroTech J570 motor was assembled at the field with ease and appeared to perform nominally on the first flight. Acceleration data shows a maximum acceleration of 13.5 g's, however this was a maximum limit for the accelerometer, so larger values of acceleration were likely felt. Figure 7 in section 3.2 shows a boost phase of exactly 2 seconds, which is close to the predicted burn time of 1.9 seconds. 1.5 grams of black-powder was used for backup motor ejection (14 second delay), although it was not needed since the altimeter performed nominally at apogee.

2.1.3 Flight Trajectory Assessment: Flight 1

The flight trajectory was vertical and the rocket appeared to be very stable during the entirety of the flight. No major deviations in the pitch of the rocket were noticed from ground, or in the downward facing video. As mentioned in the anomaly section (2.1.1), there were aggressive roll maneuvers, which caused rapid roll oscillations as the rocket tried to null roll, however the rocket clearly maintained stability, and its vertical orientation.

2.1.4 Recovery System Assessment: Flight 1

The recovery system consisted of a 24" drogue parachute which was deployed at apogee by 1.5 grams of black-powder and attached by 25 feet of kevlar cord, and a 60" main parachute that deployed at 700 feet by 2 grams of black-powder, attached by a 15 feet kevlar cord. OpenRocket simulations were ran with the rocket's exact mass and dimensions prior to flight and yielded a 19.2 ft/s descent velocity. However, onboard telemetry showed a ground hit velocity of 25 ft/s. Analysis of the onboard video shows a clean deployment of the drogue parachute at apogee, and the main parachute deployed nominally (verified visually from the ground). The large error in descent velocity was likely due to a lower than expected drag coefficient from using cheap parachutes that we obtained to minimize our budget, though we will likely optimize these for performance in the future.

2.1.5 Ground Recovery Assessment: Flight 1

Ground recovery was extremely easy for our team this year. The rocket landed approximately 200 ft from the launch pad it took off from. GPS coordinates were transmitted to the ground station throughout flight for tracking, however this was obviously not needed for recovery, although it was a nice feature to have.

Per our recovery checklist, the team lead approached the rocket with caution to verify there were no live charges on the rocket. Once it was deemed safe for the other team members the rocket was disarmed and all the electronics were turned off. The rocket was visually inspected for damage, which identified a crack in the fin fillet. Then the rocket was assembled and brought back to the judges for data and video retrieval.

2.1.6 Pre- & Post-Launch Procedure Assessment: Flight 1

Per competition rules, our team had one hour to prepare our rocket for the first flight. Our preflight checklist was thorough and aided in our capability to prepare the rocket quickly and safely, with no second guessing that we had done everything required for a safe flight. We managed to get the rocket to the RSO table in 1 hour and 2 minutes. The slight delay was due to motor assembly time, since our team had not built an AeroTech motor by ourselves in the past, so extra care was taken in handling the rocket motor for the first flight.

The post-flight procedure was not so straight-forward since we had to repair our rocket. After the rocket was saved in the field and brought back for inspection by the judges, we did a more thorough inspection on the rest of the rocket and found no further defects. To maximize epoxy dry time, we quickly drilled holes in the lower airframe of the rocket next to the broken fin fillet and injected a large amount of 5-minute epoxy into the body tube. We then taped off the rocket and applied epoxy to the outside of the fins for a crude looking, although strong fin fillet. The rocket was then placed in a vehicle with air conditioning to aid in curing the epoxy. While the epoxy dried, the flight computer was reprogrammed for flight two, and the proportionality constant that caused overly-aggressive roll maneuvers was reduced. We also re-adjusted the position of the parachutes, because we noticed that the two halves of the rocket nearly collided when the drogue parachute deployed.

Even with all the repair work, our team had the rocket ready for the second flight in under an hour and a half.

2.2 Flight 2 - Active Roll Heading Control Challenge

The second portion of the MRL competition was to perform a series of roll control maneuvers to point the camera side of the rocket to predefined compass heading directions. We approached this in a two-step process; we first nulled roll, then tracked the error in our current heading vs the desired heading and used that error to determine our control surface deflection. While there were some anomalies, our rocket appeared to hold one of the desired headings for one second prior to reaching apogee.

2.2.1 Flight Anomalies: Flight 2

Due to a field repair on one of our fins, the Badger Ballistics rocket had an even larger roll rate on the 2nd flight (see section 4, Active Roll System Analysis for more information). The roll rate was so large on this flight that it exceeded the limits of the onboard gyroscope (rated to 2000 deg/s). Fortunately (or unfortunately) we had seen this excessive roll rate during the test launch of the rocket, so code was implemented to handle this anomaly and the rocket was eventually able to null roll, and appear to hold a heading of north for one second just prior to reaching apogee. After analyzing the downward facing video, and the heading vs time data, our team feels that if our rocket had either a larger motor (allowing for more coast time), or if our fins were constructed better to reduce the natural tendency to roll, our control system would have performed the series of heading commands nominally.

2.2.1 Propulsion System Assessment: Flight 2

The AeroTech J570 performed nominally on the second flight. Plots of acceleration, velocity, and altitude (plots shown in Section 3, Actual Vs Predicted Performance) are nearly identical for both flights during the boost phase. Backup motor ejection was utilized again (14 second delay), and was not needed, since the altimeter performed nominally at apogee.

2.2.2 Flight Trajectory Assessment: Flight 2

The flight trajectory of flight two visually appeared even more stable and vertical than flight one, however, after reviewing the downward facing video footage, it was evident this extra stability was from the extreme roll rate of the rocket during ascent. The acceleration, velocity, and altitude plots (shown in Section 3) are nearly identical to flight number one, with a slight deviation in acceleration due to the induced drag from the added control surface deflection required to null roll.

2.2.3 Recovery System Assessment: Flight 2

The recovery system configuration was identical to flight one, apart from the parachute placement (discussed in flight 1 anomalies). Both the drogue, and main parachute deployment was nominal, and the rocket hit the ground at 24.2 ft/s. This is a relatively fast ground hit velocity, and if we had an extra parachute, we would have used it, however, our field repair of the fin fillet held up, and there was no damage to the rocket after this flight.

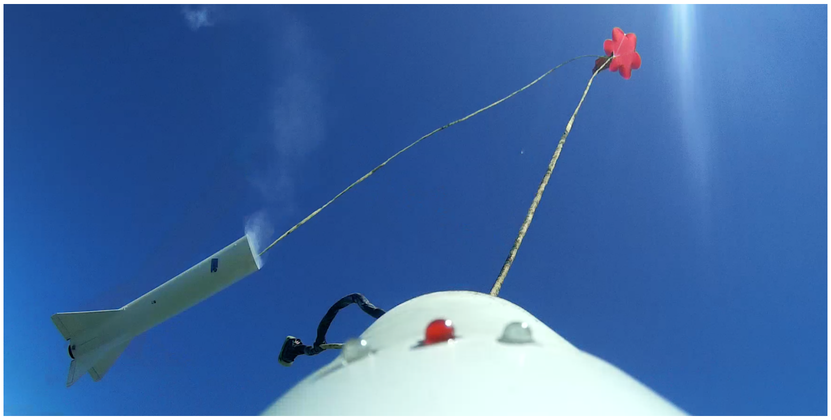


Figure 5. Drogue deployment, note that the two sections of the rocket are no longer in danger of contacting each-other

2.2.4 Ground Recovery Assessment: Flight 2

Ground recovery of the second flight was just as easy as the first flight. The rocket landed a few hundred feet away from the launch pad, and GPS tracking was not needed. There were no live charges on the rocket as the team lead approached the rocket, and there was no physical damage to the rocket upon recovery.

2.2.5 Pre- & Post-Launch Procedure Assessment: Flight 2

As outlined in Section 2.1.5, the post-flight procedure after flight one was a busy procedure, and overlapped into the preflight procedure of flight two. This was because we had to detach the shock cord and parachutes from the rocket to allow the epoxy to dry while we prepared the rest of the rocket. To accompany this change, we still followed our checklists, but had to go out of order than we originally intended. To ensure we followed every step, we double checked each step on our checklist as a final precaution before proceeding to the RSO table.

The post flight procedure went without a hitch. The rocket was recovered a few hundred feet from the launch pads, disarmed, and inspected with no defects being noted.

3.0 ACTUAL VS. PREDICTED PERFORMANCE

The predicted performance of the Badger Ballistics rocket was accomplished almost entirely using MATLAB and equations derived by the team members. This gave the team more versatility in their computer code to parameterize and adjust key variables to suit their needs. Furthermore, the predictions from the computer code outperformed the widely used commercial software OpenRocket in every aspect during the boost, ascent, and coast phase. OpenRocket was however used to predict descent velocities, although this could have been incorporated into the MATLAB code relatively easily.

3.1 Peak Altitude Comparison to Expectation

The predicted altitude for both flights was 2938 ft. Our team came into this competition knowing we would be slightly short on altitude. This was because our attempts to shed weight on our rocket proved to be insufficient, and the J570 simply didn't have enough impulse to get the rocket to 3000+ ft. Alternative motors were an option, but our team was short on funding this year, so we didn't have the option to get a different motor casing.

Figure 6 shows the predicted and actual altitude vs time. As can be seen from the plots, the two flights appear almost identical, differing in altitude by only 8 feet. Flight one had an apogee of 2530 feet, with a coast time of 10.2 seconds, and flight two had an apogee of 2522 feet, with a coast time of 10.2 seconds. This yielded an error of approximately 16 percent with respect to the theoretical prediction. Much of this error is likely due to the induced drag of the control surfaces during the roll control phase.

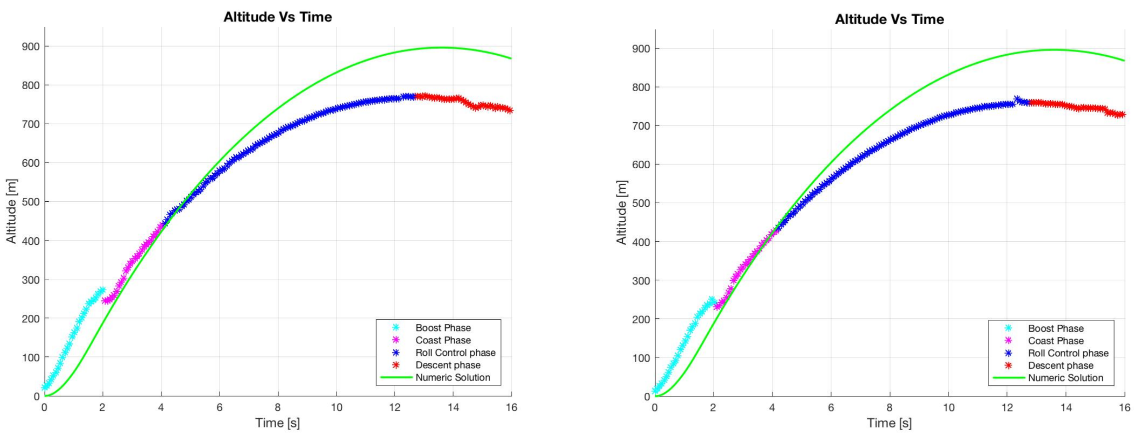


Figure 6. Theoretical vs Actual: altitude vs time. Left: Flight #1, Right: Flight #2

3.2 Peak Velocity and Peak Acceleration Comparison to Expectation

Acceleration was measured by an onboard accelerometer and recorded at 14 Hz. Figure 7 shows the absolute value of the predicted vs actual acceleration vs time for both flights. It is evident in both plots that the acceleration during the boost phase reaches a maximum value of 13.5 g's, this was due to a hardware limitation of the rocket's accelerometer, which indicates the rocket likely achieved greater acceleration than reported. One interesting thing to point out is the acceleration of the second flight. In this plot, there is a clear deviation from the predicted values at two and four seconds into flight. Since this is a plot of the absolute value of acceleration, this means that the rocket was experiencing greater negative g-force during these times. This is likely due to the fin repair, which caused the rocket to have a high roll rate, which induced more drag on the rocket throughout the entirety of flight. Then at 4 seconds in flight (2 seconds after burnout), the roll control system engages and there is another spike in acceleration, indicating even more negative acceleration from drag. From a physics standpoint, this is very interesting because it shows just how much drag force is induced in a rocket when a fin is not perfectly aligned.

The velocity of the rocket was not measured experimentally in flight, however the slope of the altitude vs time plot gives an indication of the average velocity. Measuring the slope just prior to motor burnout yields the average maximum velocity, which computes to 285.66 and 270.2 mph for flights one and two, respectively. Figure 8 shows the theoretical velocity vs time, which resulted in a maximum velocity of 298.73 mph, yielding an error of 4.58% and 10.55% for flights one and two respectively.

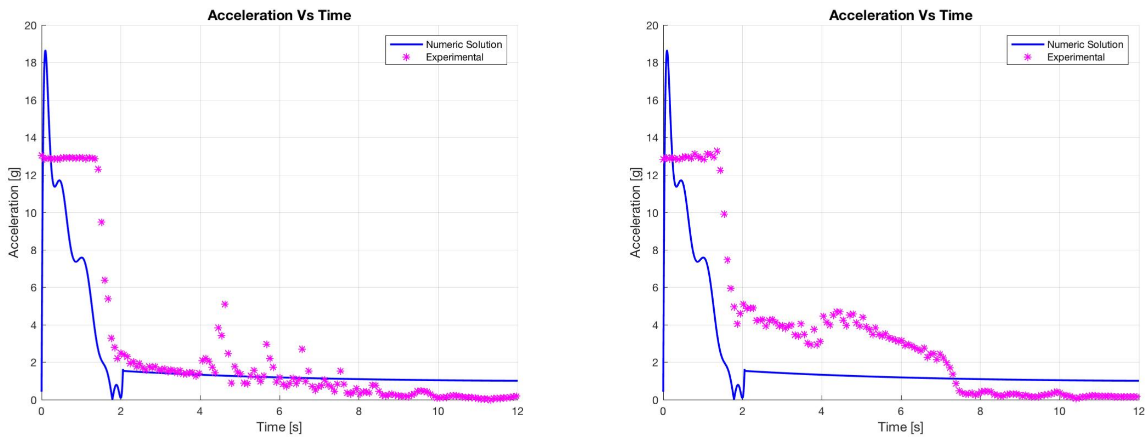


Figure 7. Actual Vs Theoretical: Acceleration Vs Time. Left : Flight #1. Right: Flight #2

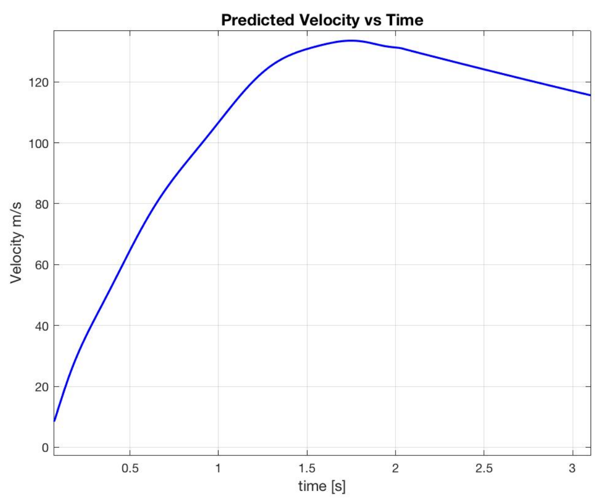


Figure 8. Theoretical velocity vs time

3.3 Recovery System Performance and Descent Velocity Comparison to Expectation

The recovery system performed nominally for both flights except for two minor hiccups. The first anomaly (outlined in Section 2.1.1) had to do with the parachute mounting location. The drogue and main parachute were initially mounted at approximately the midpoint of the shock cord, which resulted in the nose cone contacting the upper assembly of the rocket when the main parachute deployed (can be seen in video). This mounting location was adjusted prior to the second flight to reconcile this. The second anomaly was the descent speed on both flights, which were both slightly greater than 24 ft/s. OpenRocket predicted a descent velocity of 19.2 ft/s, however we were initially using a 60” fruity-chute, which had a much higher drag coefficient than a standard nylon parachute. Attempts were made to reduce the mass of the rocket prior to the competition, however this was still insufficient. Improvements for the future would include a more detailed analysis of descent velocity, as well as drag coefficient testing for parachutes.

4.0 ACTIVE ROLL SYSTEM ANALYSIS

4.1 Roll/Orientation Monitoring Data

Roll rate, and orientation data was obtained by a Bosch BNO055 orientation sensor. A gyroscope recorded angular velocity, and a magnetometer recorded heading based on earth's magnetic field. Visual monitoring was obtained by an aft facing video camera and three color-coded LEDs. During the pre-launch phase the LEDs blinked on and off every 0.2 seconds, once launch was detected, the LEDs were on constant (shown in Figure 9). Two seconds after motor burnout the LEDs performed as a visual aid by indicating the output of the control surfaces of the rocket. The green LED corresponded to the rocket trying to roll clockwise as seen by the downward facing camera, blue indicated counter-clockwise, and red indicated that the rocket was stable and only minor adjustments in the control surfaces were needed. This data, as well as altitude, acceleration, GPS coordinates, servo signal output, pressure, temperature, and quaternions were recorded to an onboard SD card throughout flight, as well as transmitted to the ground station in real time for redundancy, if the rocket could not be recovered.

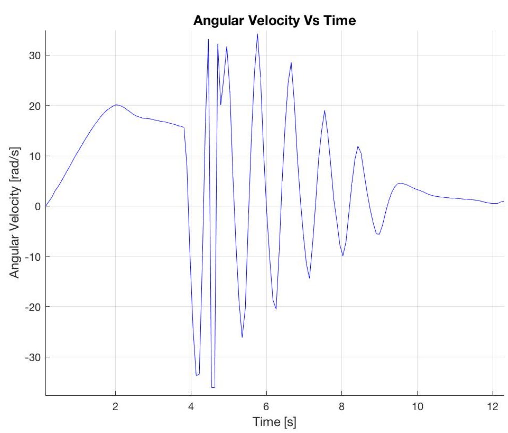
Figure 9. Downward video shows LEDs solid during boost phase

4.2 Links to Flight Videos

Flight #1: https://youtu.be/o7wd2uwsi4Q
Flight #2: https://youtu.be/cwjTEdIajFY

4.3 Data Interpretation and Comparison to Expectation

During the first flight, the rocket had a moderately high roll rate, as can be seen from Figure 10. At 4 seconds into flight the null roll function was engaged, and rapid oscillations are seen. While oscillations were expected, these were much larger than expected. Even so, the rocket eventually settles down to a near 0 deg/s roll rate prior to reaching apogee. These wild oscillations were due to a large proportionality constant, that we tuned from wind tunnel testing, but made an error in our calculations that translated the values from low speed testing (35 mph) to flight (~300 mph). To reconcile this our team did a quick calculation, and scaled down this value for second flight, however, due to a much higher roll rate from a fin repair between flights, the roll rate of the rocket exceeded 2000 deg/s, which is the erroneous data shown in Figure 10, where the angular velocity jumps from 35 rad/s to -35 rad/s. However, clever programming in the flight computer essentially told the rocket to ignore this data and to continue to null the roll. From this plot, you can also see that once the rocket passes through 0 rad/s it gently holds a near zero roll rate without the rapid oscillations from flight #1.



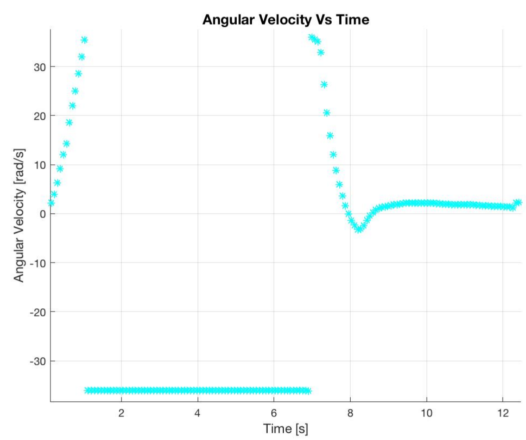


Figure 10. Left: Angular Velocity vs time for flight #1, Right: Angular Velocity vs time for flight 2.

Perhaps more interesting is the plot of the Heading Vs Time from flight 2 (Figure 11). During this flight, the rocket was supposed to first null the roll after motor burnout, then roll clockwise to North, and hold for one second, then roll counter-clockwise to 270 degrees West for one second. From Figure 11, the heading vs time seems wild until 7.8 seconds in flight, when the roll finally starts to reach zero, then the rocket does a slight oscillation between 360 degrees North, and 0 degrees North, from 7.8-8.8 seconds. This indicates that the rocket held the desired heading for one second as required! Then the rocket was commanded to roll counter-clockwise to 270 degrees West, however, it can be seen from the downward facing video that the rocket was reaching apogee during this phase and didn't have enough control to hold the second orientation.

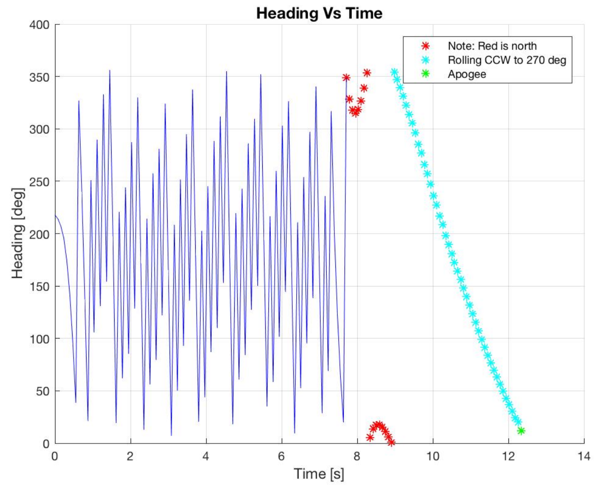


Figure 11. Heading vs Time, flight #2, note that rocket holds North for one second prior to apogee

5.0 BONUS CHALLENGE

Our team chose to transmit data from the rocket to the ground station throughout flight for the bonus challenge. We successfully transmitted and obtained angular velocity, compass heading, altitude, pressure, temperature, GPS coordinates, servo signal output, acceleration, and quaternions at over 14 times per second for both flights. We also plotted this data in real time with a telemetry GUI that communicated with the rocket over serial communication (Figure 12). Our team thinks this can be a very useful software for future high powered rocket flights, so we will continue to expand on this development (mainly addressing hardware limitations, such as maximum acceleration and maximum angular velocity limits) and will be printing computer boards (PCBs) to miniaturize this flight computer for future projects.

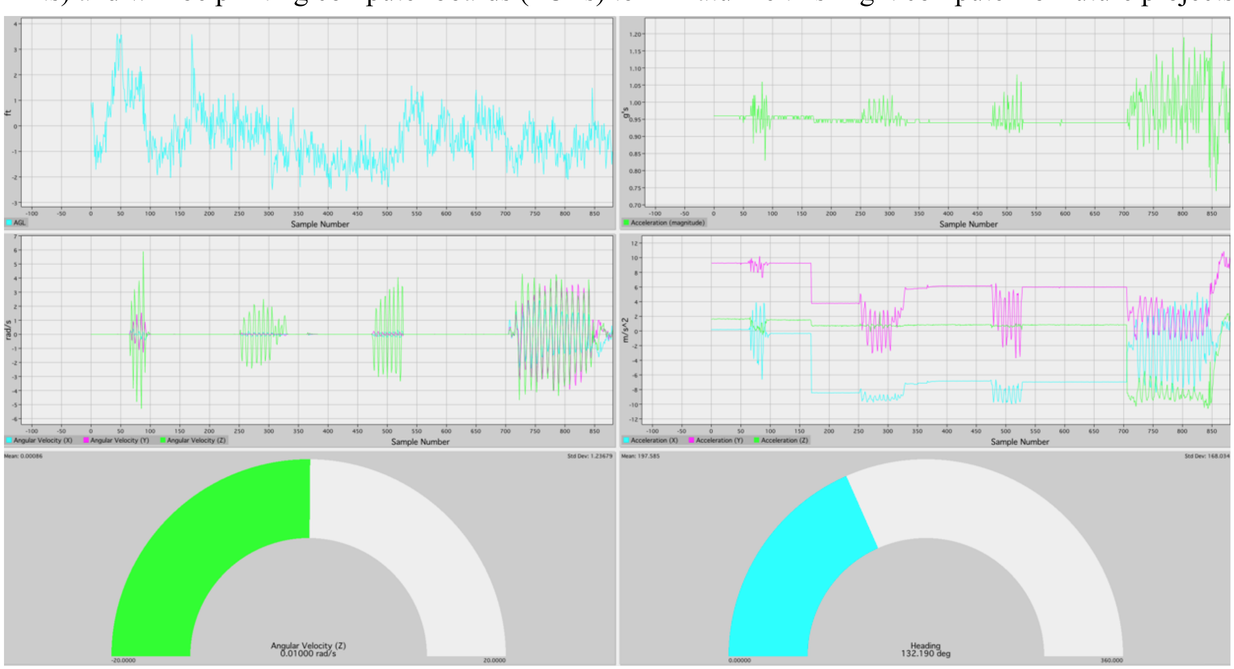


Figure 12. Live telemetry interface with various flight characteristics displayed graphically.