Flight Readiness Report for the Midwest Rocketry Competition

Team: **SEDS TnTech**
Rocket Name: **Aquila II**

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Summary of Design

Aquila II is a low-altitude, fiberglass rocket. It’s length is 2.2 m and its dry mass is 5.91 kg. Aquila II utilizes cold gas thrusters to both maneuver and stabilize itself on its roll axis. The rocket’s commercial altimeter is a StratoLogger C. Aquila II’s flight computer uses two Teensy 3.6 Microcontrollers; one to manage air to ground communication and pursue the bonus challenge, and another to manage the functions of its roll control system and log data in an SD card. The latter, the Teensy 3.6 Flight Controller (TFC), will read data from the Inertial Measurement Unit (IMU) and then use that data to determine what direction the rocket is facing, sending all data to the Teensy 3.6 Flight Recorder (TFR) via a serial port. All flight controllers are housed in the AV-bay in the nose cone of the rocket.

Budget

Table 1: *Budget Listing*

Item	Price
Jolly Logic Chute Release	$130
2x Teensy 3.6	$29
MPU9225	$15
2x XBee Pro	$38
StratoLogger CF	$55
Parachutes (24” and 72”)	$150
RunCam 2.0	$80
Fiberglass Body Components	$315
Fiberglass Nose Cone	$59
Motor Casing	$70
2x Test Motor	$190
3x Solenoid Valves	$33
Air Tank	$50
Pressure Regulator	$180
Epoxy	$10
Miscellaneous Electronics	$50

Miscellaneous Hardware	$50
Travel Expenses	$1,900
Lodging Expenses	$500
Total Expenses	**$3,879**

Fewer controllers and IMUs were required than in the originally design. In addition, cheaper antennas were found to be suitable for use both on the rocket and on the ground station. Due to flow rate and pressure rating compatibility, much less expensive valves were used with a much more expensive pressure regulator. Finally, the fiberglass airframe components used in the final design were more expensive than the equivalent carbon fiber filament which was planned to be wound into body tubes.

Construction of Rocket

<u>The Fin Can</u>

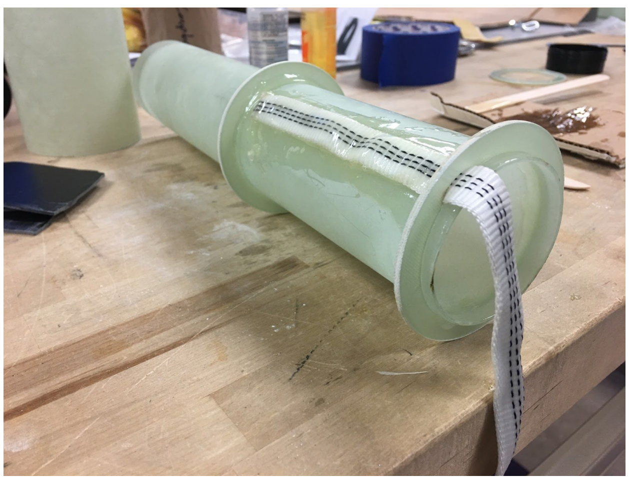
Construction began with the fin can. Having thoroughly simulated the rocket in multiple configurations, a fin shape had been chosen and was cut from 1/16” fiberglass sheet. This was accomplished by covering the sheet in blue painter’s tape and drawing the fin shape directly onto the tape. Rather than use a stencil measurements of root chord, tip cord, sweep length, and height were taken from OpenRocket, and then used to draft the shape with a ruler. This eliminated any error due to “stencil drift” (when a stencil shifts slightly during tracing). Fins were cut from the sheet in a single cutting session, and afterward were bundled together for sanding to create uniformity.

The airframe tube had been pre-slotted by MadCow Rocketry and the alignment of the fin slots was confirmed by placing the body tube in a channel of extruded aluminum, and drawing a line from the left-upper corner of the fin slot to approximately 12-14” above the slot. This allowed us to sight down the line and verify that the slot did not deviate right or left. All slots appeared to be within 0.2mm of alignment at both leading and trailing edge. All

slots required light sanding for fins to slide into place.

Before fins could be attached, the Motor Mount Tube (MMT) had to be assembled. First, the 30” tube we ordered had to be cut down to 12” and the centering rings had to be dry fitted to the tube. All centering rings required sanding to slide onto the MMT. This was accomplished using a Dremel with a sanding wheel. Light, circular passes around the inside diameter of the ring resulted in a uniform removal of material. One ring was sanded slightly too much on one side, resulting in a raised area between the ring and the surface of the tube. This ring was chosen as the forward ring, and the oversanded area was notched so that our shock cord to be epoxied to the MMT.

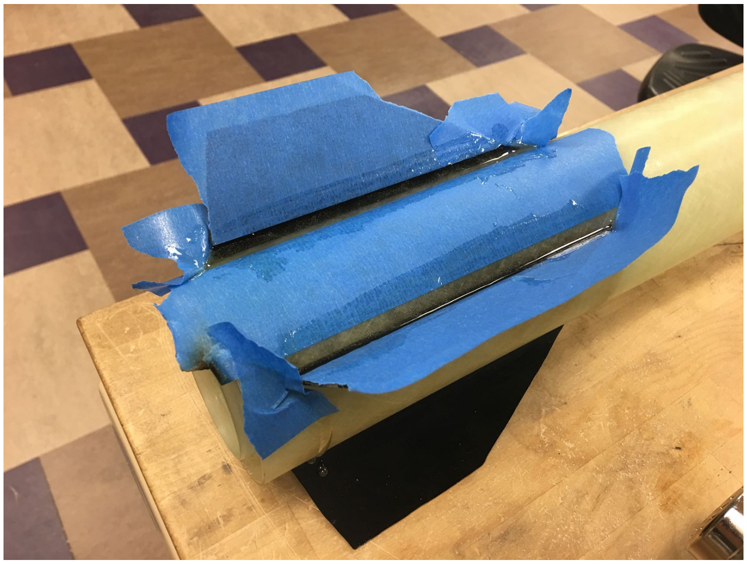
The MMT was assembled by first attaching the shock cord to the motor mount tube. 15 minute Bob Smith Epoxy was used to saturate our 20’ x ⅝” tubular nylon shock cord and bond it to a 5” sanded strip of the MMT. Afterward, the centering rings were slid into place for a final dry fit. An aeropack motor retainer was also included in this dry fitting process as it would be necessary to verify that the calculated amount of MMT aft of the rear centering ring would be sufficient to mound the retainer. The distance between the retainer collar and the after centering ring was ~1mm. In our design this gap was considered “variable” as the amount of MMT protruding from the rear of the rocket was to be a fixed value of 7mm (¼”). The Aft centering ring would be positioned such that it rested on the trailing edges of the fins.



Using the dry fitting measurements, the middle centering ring position was finalized, and both the forward and middle centering rings were permanently epoxied into position. After this, a cardboard alignment guide was made, and the fins were tacked into place using epoxy. The whole assembly was allowed to cure overnight.

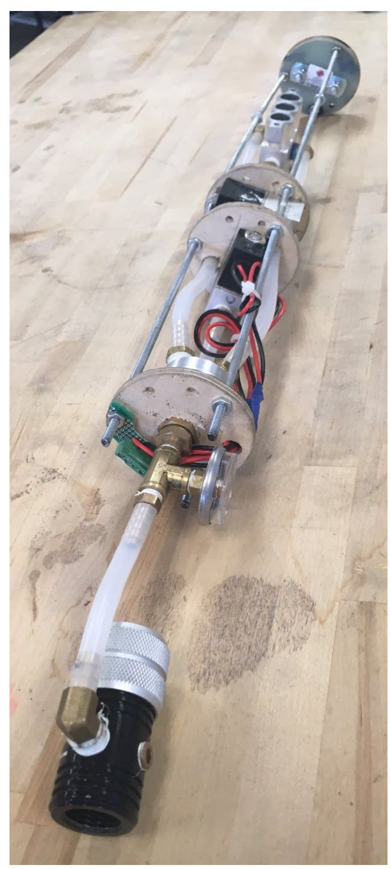
Before the rear centering ring was installed, a layup of 6oz fiberglass was applied to the space between the MMT and the airframe tube. Six separate layups were performed. Beginning on the surface of the MMT the cloth would climb the entire of length of the fin root, and then spread across the inner surface of the airframe tube. This operation took several hours, and was not “pretty” when finished. Small strands of fiberglass fibers seemed to stick out in the oddest of directions, and obscured much of the work that had been done. However, closer inspections showed that the fiberglass did in fact wet properly, and the innards of the fin can were now heavily reinforced. Subsequent weighings of the fin can showed that we had come in well under or weight budget, even after external fillets were applied.

After the fiberglass had cured overnight, the fins were measured, marked, and taped off for fillets. Once again, Bob Smith 15 min epoxy was used. Small batches of epoxy, slightly larger than a half dollar were squeezed from their tubes and applied using a large tongue depressor. A heat gun was used to accelerate the curing process by warming the fiberglass below the fillet and the fin itself. The heating of those elements helped the fillets to cure "inside first", and helped make sure that the most critical part of the bond, where it attached to the surface, solidified properly in-case the part was handled prematurely and the joint accidentally weakened. Also, we're just impatient and didn't want to spend all day watching glue cure.



With the fillets in place, the rear centering ring was installed, and the Aeropack motor retainer JB welded into place. The fin can was "done".

Pneumatics sections

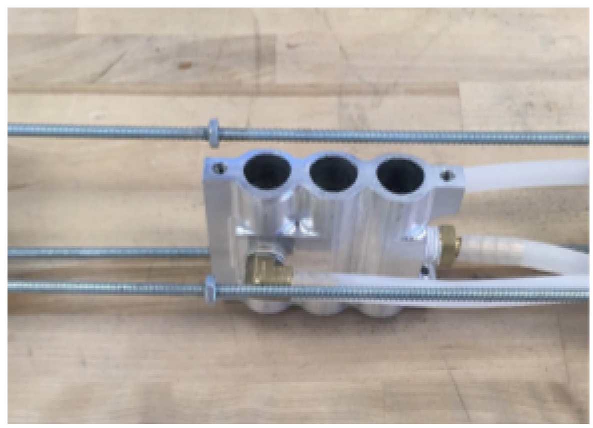


The pneumatics section of the rocket is composed of two body tubes, and two couplers. The lower airframe tube is 24" long and is permanently bonded to a 9" coupler with 4.5" of that coupler protruding from the bottom of the airframe. The lower 4.5" of this coupler is designated as a commercial avionics bay, as all of our recovery hardware is contained in the Fin Can. The arrangement will be discussed in greater detail in a later section. The coupler is bisected by a fiberglass bulk plate which is reinforced by three separate 1"x ¾"x ¼" tabs of 5-ply birch hobby plywood. This reinforcement is critical as this bulk plate is responsible for supporting the weight of the entire forward section of the rocket during recovery. The AV bay is sealed with ¼" plywood bulk plate with is backed by a 1/16" fiberglass bulk plate. This "lid" is drilled in four places to accept the threaded support rods for the pneumatics assembly and a wiring path for ejection charges. The lid is also where we have attached a ¼" u-bolt which is used to attach recovery hardware.

The upper section of the coupler is part of the pneumatics assembly. In order for the Nozzle pods to actually integrate with the rest of the system, they must pierce the wall of the airframe several times. In total, there are ten holes. Six are ¾" across, and four are ⅜" across". These holes would weaken the airframe considerably if its thickness were not doubled by the coupler which is epoxied to the body tube in these locations.

The actual pneumatics components are supported by three 10-24 threaded rods which run nearly the entire length of the lower section, and are arranged in a triangular configuration. These rods support the system using a set of three, ¼" Birch plywood bulkheads. These bulkheads are held captive by nuts on either side. The lowest bulkhead supports the two directional control solenoids, and the middle bulkhead supports the emergency dump solenoid. The upper bulkhead supports the weight of the 3 way splitter which divides airflow to each solenoid.

Below all of this, and supported by the mounting screws which pierce the airframe and retain the nozzle blocks, is the custom aluminum distribution manifold. This was custom milled here at tech and was designed by a member of our team. The upper channel is designated for the dump valve. The lower two channels require a ninety degree barb adapter. For this reason, they were chosen for the directional control solenoids. Keeping the gas pathways similar was deemed vital to ensure that one direction of roll was not more powerful than the other.



Aluminum Distribution Manifold

Weights of these components are in the **Table 2** below.

Table 2: *Pneumatics component weights*

Item	Quantity	Mass	Mass Sub-total
Regulator	1	216	216
Solenoid	2	123	246
Dump Solenoid	1	123	123
Barbs	11	16	176
3-way	1	140	140
Distr. Block	1	147	147
Coupler	1	0	0

Nozzle pod	2	54	108
Tubing	31	0.5	15.5
#10-24 nuts	30	3.1	93
#10-24 rods	3	50	150
Total			**1414.5**

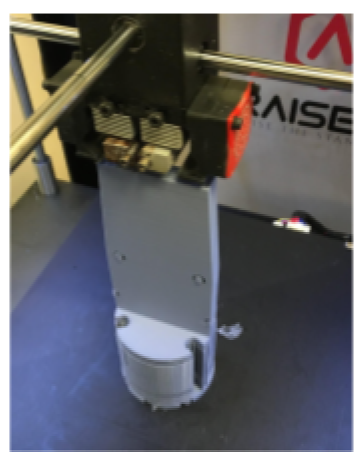
During boost, the the rods are under compression, and the load is transmitted to the reinforced coupler bulk plate by nuts adhered in place using thin CA glue. During recovery, the rods are under compression and are supported by the lower ave bay lid.

The Upper Pneumatics Section is 17 ¾” long and houses the 3000psi HPA tank that feeds the control system. Like the lower section, It is glued to its lower coupler. Inside this coupler, a fiberglass bulk plate is epoxied into place at the midpoint. Epoxied in place just above this, is the 3d printed cradle for the tank. The tank is slid into position from above, and once rested in place, the low pressure regulator (LPR) is screwed into place below the cradle. After this is accomplished, the tank retainer is installed from above. The tank retainer is an aluminum cross ⅜” thick. On the outer edge of each are of the cross there is a threaded hole which allows us to screw four #8 machine screws through the airframe and into the retainer, holding it in place. The upper and lower sections of the Pneumatics section are held together by #8 machine screws threaded directly into the fiberglass.

Above the tank retainer is a small (2 inch tall) space for wiring. This space is also where the tri-color led pierces the side of the rocket, just below the camera mirror shroud. Above this wiring space is a single hole for the camera to peer through, and a pair of shrouds. Only one shroud is functional as it holds the mirror that allows the camera to see downward.

AV-Bay Section

The AV-Bay was constructed using a 3D printed frame. The frame provides a mounting point inside of the nose cone to mount the components. Prototyping perfboards were used for both the TFC and TFR to connect the Teency 3.6s to the other compents in the circuit. The perfboard also provided mounting point to mount the circuit boards to the 3D printed frame. The AV-Bay is split into two sections by a bulk plate. The bottom section contains the power system and the camera. The power



3D printing the avionics sled

system consists of two lithium polymer batteries, a bat-share system, and a buck converter. The upper section of the AV-Bay contains the TFC, TFR, the IMU, the presser sensor, the XBee and the antenna for the XBee. The antenna for the Xbee is placed at the very top of the AV-Bay as far away from the other electrical components to prevent interference. The TFC contains four H-bridge ICs to produce a 5hz PWM signal with a peak to peak voltage of 12V. This signal is used to open the solenoids.

Photos of Completed Rocket

Fully assembled rocket

AV-Bay

Nosecone

Fin Can

Nozzle block

Roll Control

Aquila II's angular roll is measured with a MPU9225 inertial measurement unit (IMU). The IMU returns the rocket's angular velocity about the roll axis, and the software of the Teensy Flight Controller (TFC) numerically integrates the velocity using the trapezoidal rule to obtain its current angular. The process runs each time through the main loop is and can be represented by the equation:

$$\theta_{current} = \theta_{last} + \left(\frac{\omega_{current} + \omega_{last}}{2}\right)(t_{current} - t_{last})$$

Where ω is the angular velocity measured by IMU and θ is the angular position. Both ω and θ are initialized to 0 when the IMU's accelerometer detects liftoff. At the beginning of each loop, the "current" variables are determined by reading the IMU or the TFC's clock, and at the end of each loop the "last" variables are set equal to the "current" variables. An additional limit is placed on θ that it can never be more than 180° from the setpoint, or the position the rocket should be at. If this occurs, the TFC either subtracts or adds 360° to θ not changing its position but changing how it thinks about its position. This ensures that the rocket will always take the shortest path to its setpoint. For example, if it's at 270° and the setpoint is 0°, it will change θ to -30° so that it only has to move 30° in the positive direction instead of 270° in the negative direction.

The TFC attempts to implement a PD (Proportional-Derivative) control algorithm. This means that the output to the actuating elements (in this case, the solenoid valves and nozzles) is made to have components proportional to both the error and the derivative of the error, as shown in the equation below:

$$Output = K_p * error + K_d * \frac{d}{dt} error$$

The error is calculated by subtracting the rocket's current position from the setpoint. The derivative error calculation is slightly more complicated; while it could be calculated by numerically deriving the error, this has the potential to be very noisy and drive the system unstable. Instead, it can be calculated as follows:

$$error = setpoint - \theta$$
$$\frac{d}{dt} error = \frac{d}{dt} setpoint - \frac{d}{dt}\theta$$
$$\frac{d}{dt} error = \frac{d}{dt} setpoint - \omega$$
$$\frac{d}{dt} error = \frac{setpoint_{current} - setpoint_{last}}{t_{current} - t_{last}} - \omega$$

For most of the rocket's flight, $\frac{d}{dt} setpoint = 0$, and therefore $\frac{d}{dt} error$ can be found by taking the negative of the angular velocity measured by the IMU. When the setpoint does change, an additional numerical derivative term picks up the change, as shown above; however, since this term would immediately go back to 0 in the next loop and these loops occur much faster than the control cycle. To solve this issue, the TFC keeps a rolling average of the derivative error, resetting the sum and number variables at the end of each control cycle. The final derivative error calculation is thus:

$$\frac{d}{dt} error = \frac{\Sigma\left(\frac{setpoint_{current} - setpoint_{last}}{t_{current} - t_{last}} - \omega\right)}{number\ of\ loops}$$

The output to the valves is a software-generated, pulse-width-modulated (PWM) signal with a period of 0.2 s. The relatively long period was chosen to ensure that the opening time of the valves (10 ms) was less than 10% of the total period. Every 0.2 seconds once control is enabled, the percent of the period that the valves are on, or the duty cycle, is set to:

$$Duty\ Cycle\ = K_p * error\ +\ K_d * \frac{d}{dt}error$$

Where K_d and K_p were chosen using simulation and testing to be 1.0 and 0.25 (with angles in radians). This roughly approximates an analog force using a digital signal. If the duty cycle is calculated to be negative, the controller simply writes the equivalent positive duty cycle to the valves in the opposite direction. The duty cycle is also limited in the code to -100% to +100%, since a valve cannot be on more than 100% of the time, and set to 0 when it is in between -5% and +5% in order to avoid noise when the rocket is relatively close to its setpoint.

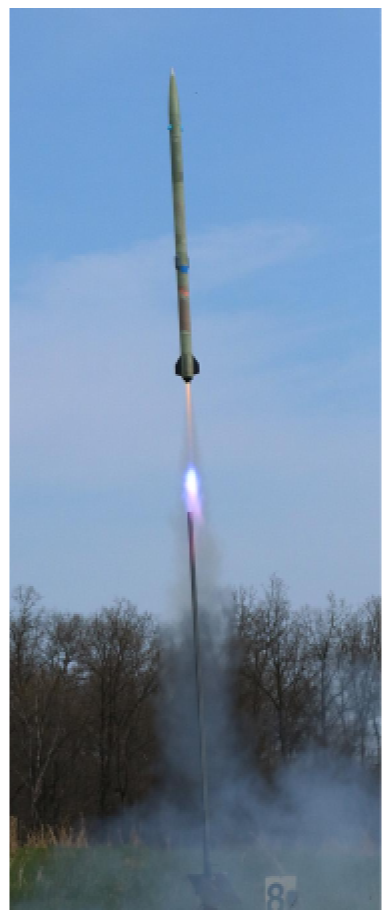

Hanging test of control system

The control algorithm was tested prior to launch by hanging the portions of Aquila II containing the pneumatics and electronics systems from a ladder, pressurizing its pneumatics, and enabling the control commands. Fishing line, snap swivels, and bearings were used to create the hanging rig in order to reduce the rotational force on the rocket, although a small constant torque was still found to be applied by the fishing line. The simulink model of the rocket in flight was modified in order to account for this force, as well as the rocket's lower mass and the reduced damping due to the lack of the fin can. The model was then used to formulate new control gains, resulting in a proportionally much higher K_d. In this way, the goal of the testing was not so much to ensure that the flight ready rocket worked as that the algorithm, pneumatics system, and conceptual components of the simulation worked. Further tests were planned to occur after a successful test flight.

Tests were performed both of the rocket's ability to maintain a position and to actuate to a commanded position. It showed an excellent ability to do the former, but quickly went unstable from its own actuation when trying to accomplish the later. This issue was solved by lowering K_p and K_d, but further issues arose due to low battery voltage and the rocket was not able to demonstrate full roll control. As mentioned previously, further testing is planned to take place using fully charged batteries, implementing the lower control gains, and with the fin can fully incorporated.

Test Flight 1

Test Flight 1 Launch Team, post-recovery



Test Flight 1 Liftoff

Our first test flight was on April 21st and occured at the Launch Crue field in Holland, Indiana. For this fight, radio communication was not active. The goals of the test were to demonstrate roll stabilization, record IMU data in flight conditions, test the structure of the airframe, and test the recovery system. Unfortunately there was a full electronics failure before the motor was ignited. This meant there was no roll stabilization and no IMU data recorded during this flight. It is not certain what caused the failure, but is possible there was a power system failure or that a reset button was accidentally pressed during assembly.

To prevent this failure from happening again, wire terminals were added to the bottom of the AV-Bay to simplify the assembly process, and an Xbee communication system with the ground station will be present at all launches to ensure flight controllers are operational before the motor ignited. Although the flight control system failed, the recovery system performed nominally for this flight.

The video of our first test flight indicated significant instability in our rocket. After the leaving the rail, it listed hard to the side, and continued to rotate until enough propellant had been burned that stability had been achieved, and the rocket carried forward in the direction it was pointing when it became stable. Utterly puzzled, we tore back into our simulations and discovered two great flaws in our predictions.

The first is that we had not accounted for the change in CP that our mirror shrouds would make. Our predicted stability margin from the night before launch was 2.9. This simulation did not include the shrouds at all. We assumed their impact would never be large enough to destabilize the rocket. Post flight modelling and analysis showed that the mirror shrouds reduced our stability margin considerably. The CP was moved forward almost a full caliber.

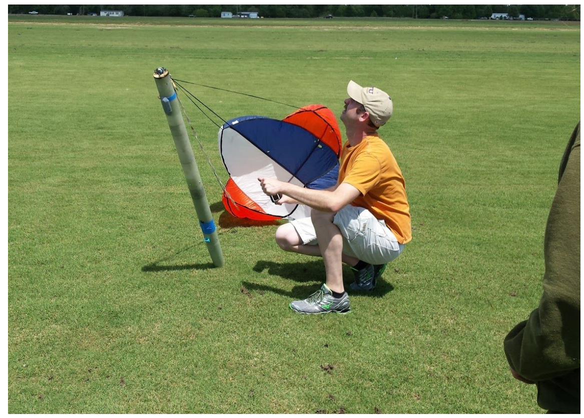
The second is that an override was performed on the mass of the upper pneumatics section without overriding subcomponents. This resulted in the simulation accounting for the weight of the tank twice… this error was not caught as it was made the night before launch when final weights were being tallied, and nose we were calculating the necessary noseweight to reach stability. Foolishly, we did not tally the actual weights on paper, we trusted what we had plugged into the software, as we had “just updated everything”. To prevent something like this from happening again, all figures from software are compared to excel spreadsheets and double verified by team-leaders. This error brought us from a perceived stability margin of 1.5 to 0.1.

The RSO check wasn’t very thorough as the RSO had basically watched us assemble it. When he examined the balance cg was still well ahead of where the CP was marked.

What saved it was the fantastic power of the Aerotech J800T. Aquila II left the pad at more than 80mph and continued straight up thanks to the incredible momentum we’d gained before leaving the rail. By the time she had turned enough to start getting into trouble, she’d attained balance, and continued upward towards the east at about 15 degrees from vertical.

To fix these issues, the fins were redesigned and the simulations were fixed. The fins are now 1” taller, and the extensions are reinforced by a double layup of tip to tip 6oz fiberglass. The proper *accurate* static stability margin is now 2.84. Simulations show we will always leave the rail at a margin of greater than 1.1.

Test Flight 2



Our second test flight was on May 6th at

The IMU accelerometer was used to detect both motor ignition and liftoff. The control was then enabled 2 seconds after burnout. Aquila II was commanded to attempt to rotate “North” (whatever orientation it had when it launched) and then hold this position for 5 seconds. While the rocket’s control algorithm would continue trying to reduce error to zero, the command code would tolerate an error of 15^{o} in either direction. If it was able to accomplish this task, it would then go through similar maneuvers in several different directions with steadily reducing hold times. After 60 seconds (more than enough time to complete the flight). The control would be disabled and the dump valve would be triggered, releasing all compressed air.

The following charts show data recorded by the TFC during the ascent stage of the launch only.

As can be seen in **Figure 1**, the TFC successfully detected liftoff and burnout using the IMU’s accelerometer. The plots labelled “liftoff” and “burnout” show boolean variables set in the code whose values were written to the SD card for debugging.

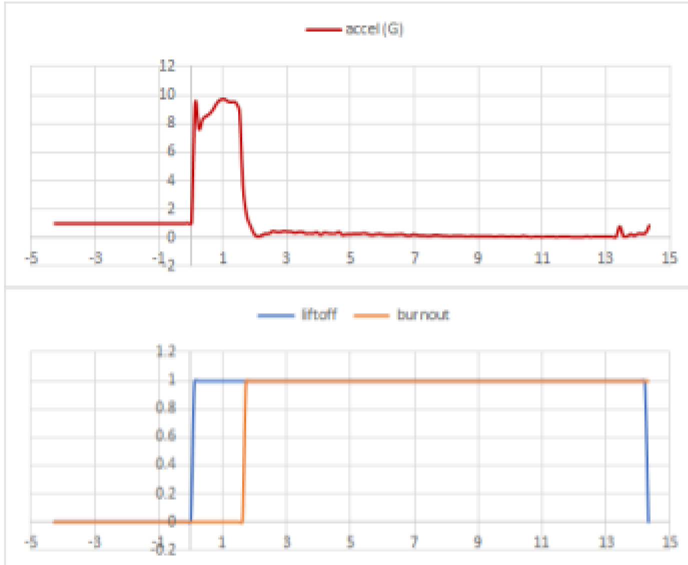


Figure 1: *Acceleration, Liftoff, Burnout*

The rocket's rolling behavior is shown in **Figure 2** and **Figure 3**. Aquila II was not able to compensate for its own intrinsic roll, and therefore the command code never proceeded to the next setpoint and spent the launch attempting to stabilize its roll. While the angular velocity was observed to decreased throughout the flight, it is thought that this is due to the decreasing linear velocity rather than the efforts of the TFC. θ, ω, and both components of the error were calculated correctly, including the 360° rollover whenever the error exceeded + or -180°.

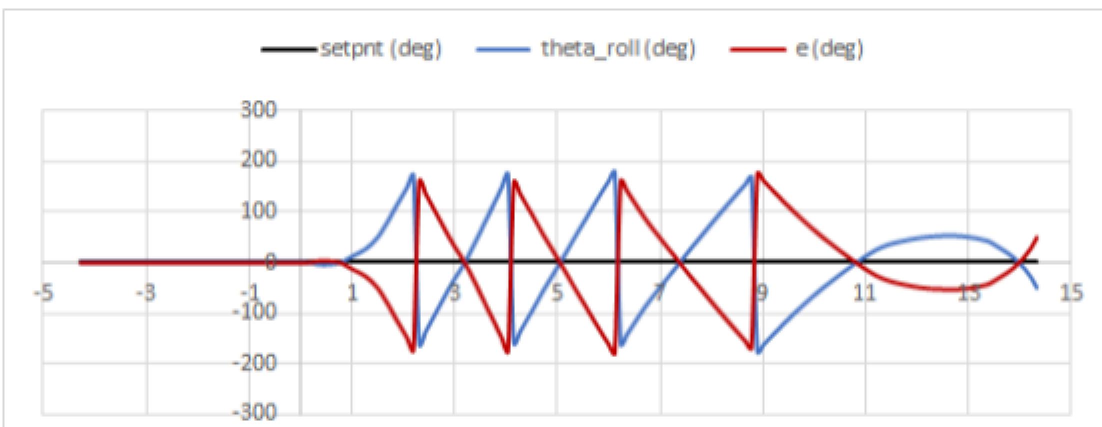


Figure 2: *Angular Position Metrics*

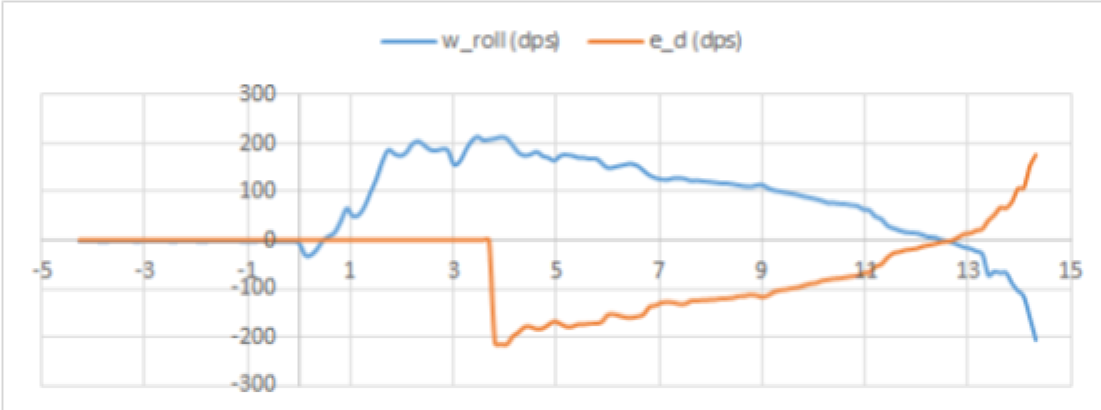


Figure 3: *Angular Velocity Metrics*

Figure 4 shows the duty cycle calculated by the TFC and written to the solenoid valves. The valves were either on 100% of the time in one direction or 100% of the time in the other, indicating that the nozzles were firing at their maximum capable thrust. This is supported by launch video showing indicator LEDs lighting up in sequence with the nozzles firing (**Figure 5**) and by the audible clicking heard once the roar of the motor has faded.

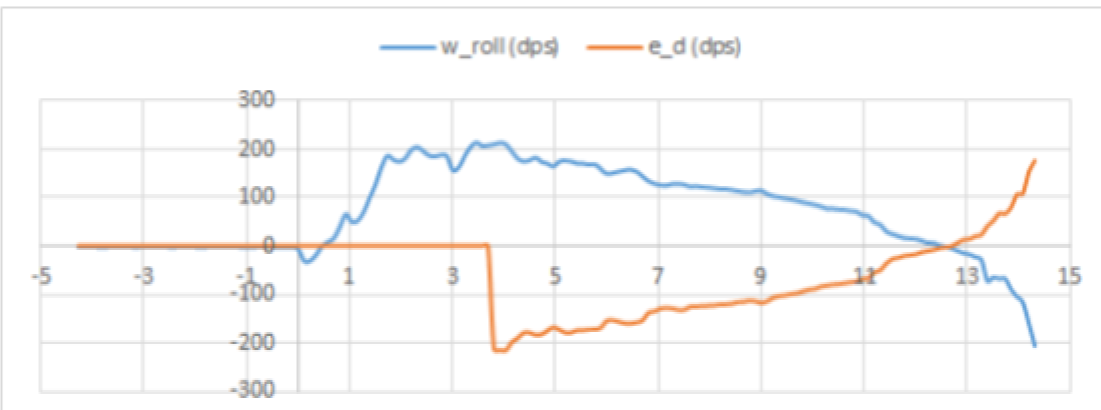


Figure 4: *Angular Velocity Metrics*

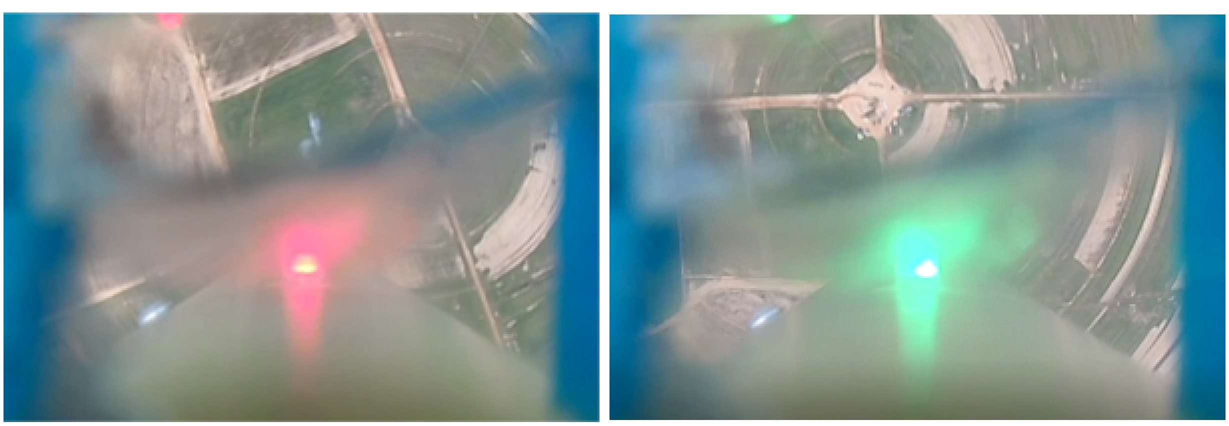


Figure 5: *Red/Green LED lights up when CW/CCW valve is firing*

After the flight, the data was analyzed further using excel. The recorded angular velocity curve was numerically derived to obtain the angular acceleration. Then, using the minimum and maximum estimates for the rocket's moment of inertia (a solid cylinder and a hollow cylinder, respectively) the net torque applied to the rocket during the flight was calculated and is shown in **Figure 6**. In addition, using force values obtained during nozzle testing, the torque applied by the cold gas thrusters was calculated and is shown in **Figure 7**.

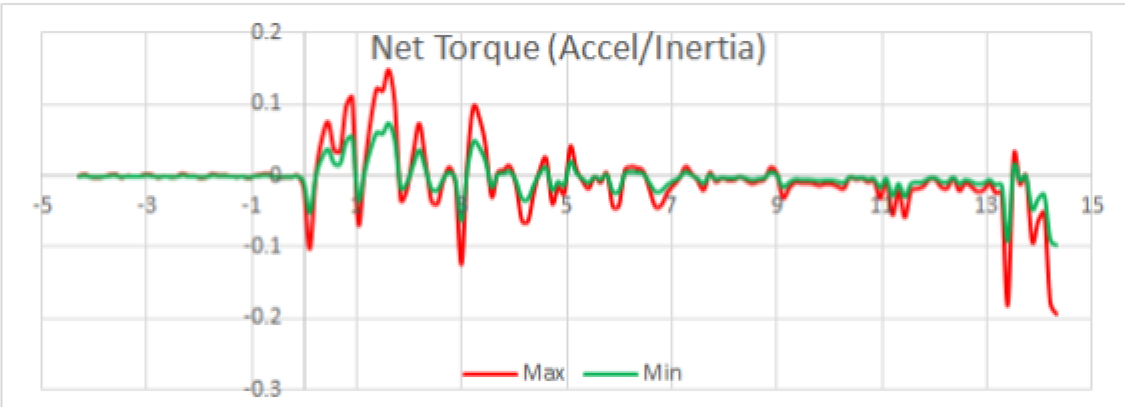


Figure 6: *Net Torque*

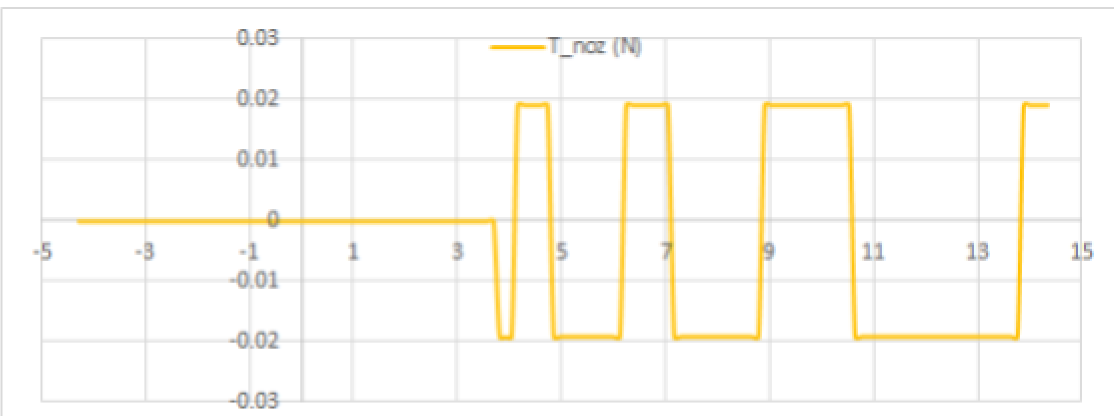


Figure 7: *Nozzle Torque*

The torque of the nozzles was therefore much less than the net torque causing Aquila II's angular acceleration, and would-be impact must have been cancelled out by an aerodynamic reaction force.

In conclusion, it seems likely that the failure to control roll is most strongly correlated to the low magnitude of the nozzle forces as compared to the aerodynamic forces on the rocket. Simulations and hanging tests were both run in absence of the high velocities the rocket would experience during flight, resulting in the acceptable performance observed therein. In addition, the 360° rollover may be causing unexpected stability problems by causing the valves to attempt to slow the rocket down when it is traveling in the wrong direction but to actually contribute to the high roll rate when it passes 180°.

Vertical Performance

Vertical performance of the rocket was lower than anticipated due to a number of reasons. Our motor selection for this launch had to be changed due to the limited availability of the Aerotech J800 at this time. We instead flew on a Loki J820 which has less impulse and lower initial thrust. The difference in impulse is approximately 15%, and the initial thrust is 20% lower. Our predicted apogee for this flight was ~2900 feet. Our actual altitude was 2520 feet according to our stratologger CF altimeter. Our own avionics suite aligns with this measurement as we reported 2550ft. At this time, I believe the majority of this discrepancy is due to our motor selection. Several elements of its configuration were out of alignment with its description in the instructions. Our reload was a single grain where the instructions indicated several, and the way that it had to be assembled required us to borrow a nozzle from the vendor we purchased it from. While this nozzle throat measured exactly what was called for in the instructions, we cannot guarantee that its design was optimized to produce the results expected in OpenRocket.

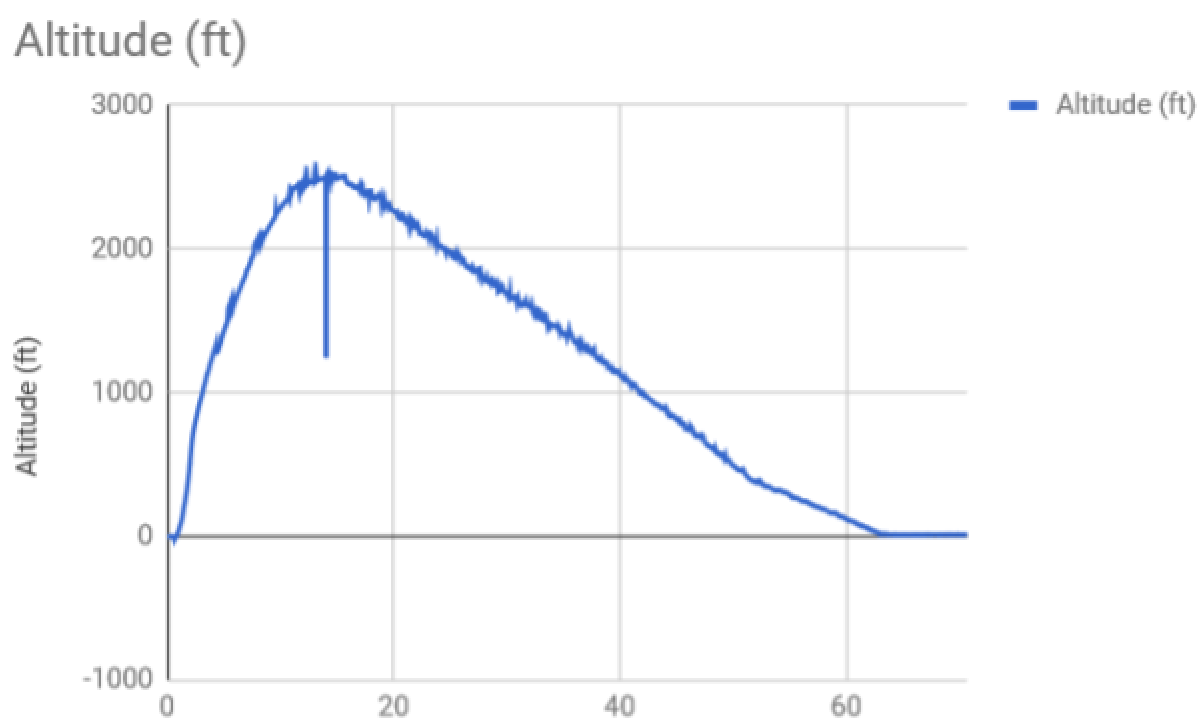


Figure 8: *Altitude vs Time*

Our descent went exactly as planned. Our rocket fell under dual 18” drogues to 500ft where our Jolly Logic Chute Release allowed the main chute to inflate. The Descent speed under drogue averaged 57.9 ft/s.

Unfortunately, 72” rocketman Chute we selected as our main is not sufficient for our needs. Our average velocity under main was 33.7 ft/s. This was calculated using samples from one second after chute was released to just before impact. We will be upgrading parachutes before the competition in Minnesota to a Rocketman 8ft parachute. We are still not sure how our 14lb rocket descended 25% faster than a 17lb rocket would, according to The rocketman website.

Planned Changes

- Increased derivative gain to increase priority of reducing angular velocity to zero
- Analyze fins to look for potential irregularities and improvement opportunities
- Investigate nozzles with capability to produce higher force
- Upgrade Parachute to larger size
- Incorporate Tracking into the Avionics package
- *PAINT ROCKET SO IT LOOKS COOL*