Preliminary Design Report for the Midwest Rocketry Competition

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

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Executive Summary

Aquila II, is a high-powered rocket that utilizes cold gas thrusters to both maneuver and stabilize itself on its roll axis. The design contained in this report is the culmination of months of research and planning toward creating a safe, effective, well-implemented, and innovative launch vehicle.

This report begins by explaining the intended mission profile of the rocket and detailing some of its performance parameters. It then moves on to the physical structure of the airframe, which is comprised of three separate body tube sections, structural supports for internal components, the fin can and motor mount, and the dual-deployed recovery system. The reasoning behind these design decisions is explained, as well as the possible negative effects of these decisions and how they were negated. A brief description is also given of the construction procedure.

Next, the internal workings of the rocket and the methods by which it will complete the mission objectives are discussed. Aquila II's avionics systems are much more complex than those for a standard high-powered rocket. Consisting of four separate microcontrollers and a myriad of support hardware, they are designed to give the rocket as much redundancy as possible for the most mission critical elements and to implement many of the necessary safety features.

The pneumatics system is the defining feature of Aquila II. Compressed air is stored in a high-pressure tank and then regulated down to a pressure compatible with commercial solenoid valves. Two valves control roll by directing airflow to four supersonic nozzles, while a third serves as an emergency pressure release which channels all compressed gas out of the system without altering the attitude of the rocket.

This design also addresses the bonus challenge by implementing a bi-directional communications system between Aquila II and the ground control system, This will allow real-time monitoring of all rocket instrumentation and computer data, the ability to program new roll orientation parameters while the rocket is on the pad, and the evaluation and transmission to ground of received arithmetic problems.

1. Mission Profile

Lift-off operations begin with the final pre-flight checks of the vehicle via radio link before sending any bonus objective data to the vehicle. Once all checks are completed and the bonus objective data is delivered, the vehicle is ready for launch. After ignition, the vehicle experiences a 1.7 second burn from its Cesaroni J760 motor, taking it to nearly mach .5 (approx 380 mph). Then, the vehicle has approximately 16 seconds of coast time to complete the mission instructions before apogee. At an estimated apogee of 3900 ft, regardless of its completion of mission objectives an ejection charge will fire, the upper and lower sections of the vehicle will separate, and an 18” drogue chute will deploy. Should the altimeter based ejection not fire, a charge built into the motor will fire 18 seconds after burnout.

Once the noncommercial avionics have detected that the vehicle is descending, they will open the Emergency Dump Solenoid Valve (EDSV) and hold it open for the remainder of the flight to eject excess compressed air. After falling from an apogee to a recovery altitude of 700ft, a Jolly Logic Chute Release will open the main parachute and slow the vehicle’s descent to an estimated 20 ft/s at landing. Recovery of the vehicle will be accomplished by a small radio transponder and a directional receiving antenna.

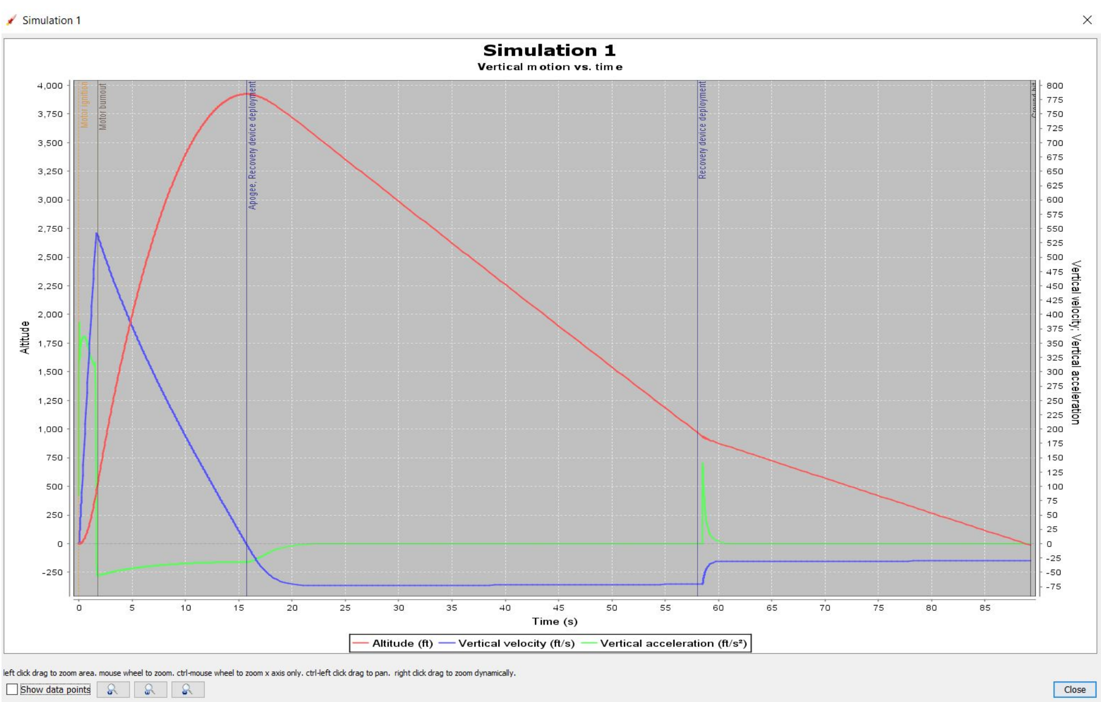

Figure 1. Open Rocket Simulation - Vertical Motion vs Time

After postflight inspection and data collection, the vehicle will be disassembled, inspected, refueled, repacked, and brought to the Range Safety Officer (RSO) tent for inspection for its next flight. Details of this process will appear in the Flight Readiness Report.

2. Airframe Design

The rocket airframe (shown in **Figure 2**) is constructed of 3” ID filament wound fiberglass tubing purchased from MadCow Rocketry. The total length is approximately 82” (2.04m) with an estimated pad weight is approximately 7.01kg.

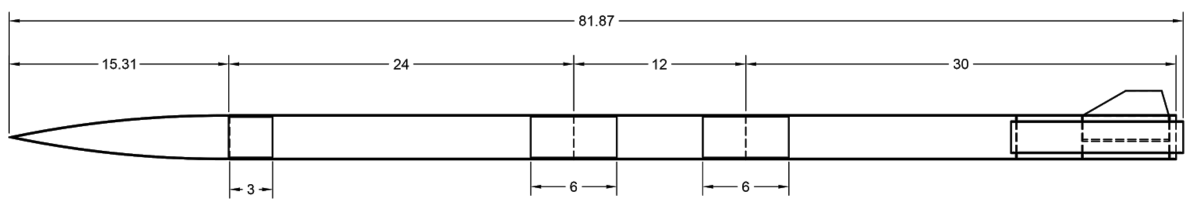

Figure 2. Full Airframe Schematic

The nose cone is a 5:1 ogive design and will be purchased from MadCow Rocketry as well. It contains 560 g of ballast in order to maintain stability of the rocket and counteract the effects of the heavyweight pneumatics components mounted lower in the airframe.

The body is split in two places, resulting in a three section airframe. The two forward sections are joined by a 6” coupler and secured together using 3mm machine screws, which prevent drag separation and excess flex. This forward joint exists solely for the purpose of servicing the pneumatic components of the rocket. The nose cone will be attached in a similar manner, as due to the nature of the rocket’s recovery system, it is not necessary to eject the nose cone during flight.

Throughout the structure, there are several 3d printed support plates that mate to the various subassemblies. The propellant tank will be supported by a bowl-shaped ring that is epoxied to the airframe, and also rests on a centering ring for extra support. At peak thrust, the propellant tank supports will be subject to in excess of twenty pounds of force, and during a severe, high-g ejection event that number could increase by several orders of magnitude, necessitating the extra support provided by the centering ring.

Above the tank will be a heavy-duty retainer system to ensure the tank stays in place. It is likely that this retainer system will be a screw in plug, similar to an aeropack retaining ring but with threads on the inside.

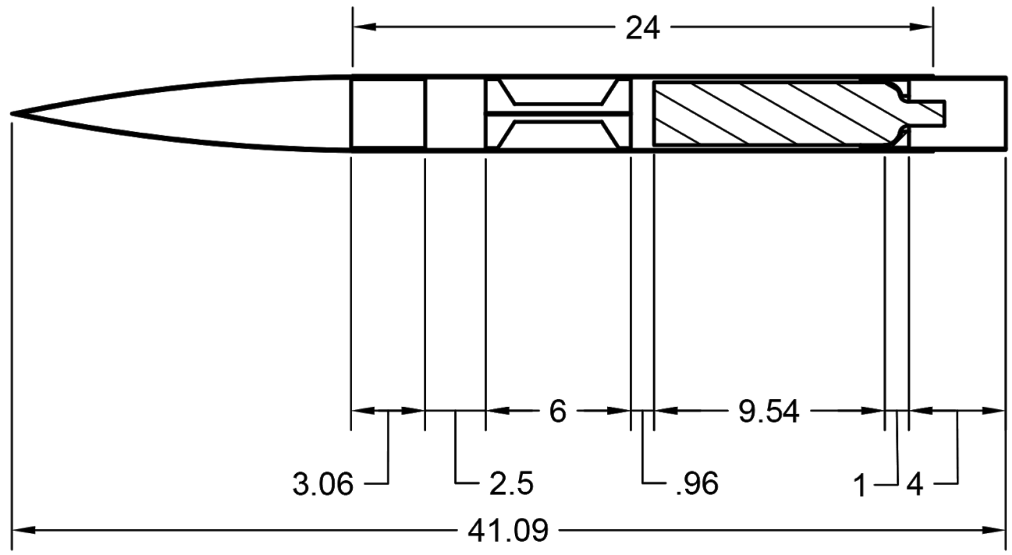

Figure 3. Nosecone/UAB/Propellant Tank Assembly

Above the propellant tank, held against a more narrow centering ring, is the Upper Avionics Bay (UAB), which contains the majority of the non-commercial avionics package. The actual physical arrangement of the components within that subassembly will be examined in following sections.

Joining the middle section to the fin can is another coupler, which will help reinforce the sections of the body tube pierced by nozzle hardware. This coupler is epoxied to the middle section and is bisected by a bulkplate in order to allow more room for the nozzle attachment points. Below this bulkplate rests the Lower Avionics Bay (LAB), which contains the commercial altimeter. In traditional form, the LAB is sealed from the fin can by a pair of bulkplates and threaded rods.

A four-fin layout is used to maintain symmetry with the four nozzles of the pneumatics control system. Each fin will be custom milled on a CNC router. Due to the rocket length necessary to house all the subsystems, the fin size required to maintain stability is quite small (see **Figure 4**). This is advantageous as it leads to a more efficient airframe for vertical performance and limits the aerodynamic resistance that thrusters are required to overcome. The root length of the fins is 6” and the height is 1.75”.

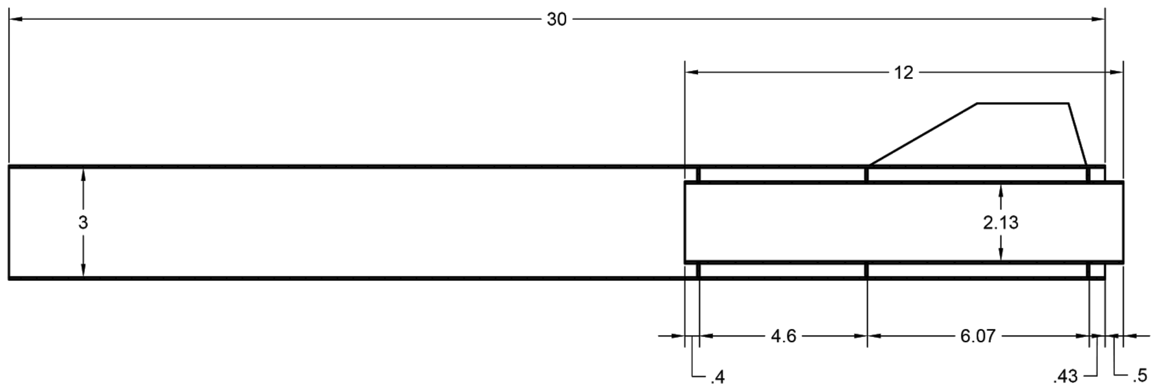

Figure 4. Fin Can/Motor Mount Assembly

The fins are attached through-the-wall to a 54mm motor mount. The size 54mm was chosen to fit the large selection of motors in the J range and to take full advantage of every Newton-Second of impulse the competition allows. The selected motor is the Cesaroni J760. Its high initial and average thrusts will allow Aquila II to leave the pad with greater stability, while its high impulse is required to lift the heavy subsystem components to the specified 3000+ feet in altitude. While not pictured in the diagram, the motor retainer used is an Aeropack 54mm standard retainer.

To construct the fin can, a single piece of epoxied fiberglass cloth will be used to fuse the motor tube, fin, and body tube together on both sides of each fin. This results in a single, continuous, internal fiberglass-reinforced fillet. See **Figure 5** for an example of this technique on a 4” rocket constructed by a team member. This technique gives incredible rigidity and strength to the entire fin can and will provide assurance that none of the three centering rings will fail during motor burn. After applying internal fillets, the aft centering ring is installed with epoxy, and then “fiberglassed” into place as described above. The centering rings are made from 1/16” fiberglass, and are also purchased from MadCow Rocketry.

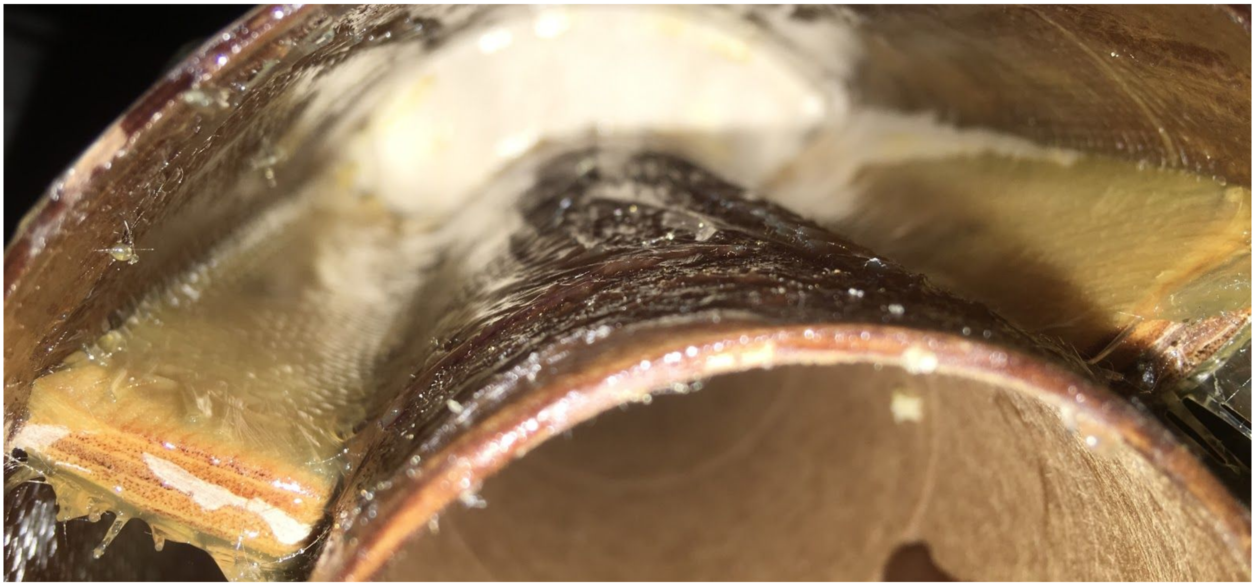

Figure 5. Continuous Fiberglass Reinforcement

Throughout the design process, Open Rocket was used to calculate stability information. According to latest simulations, the center of gravity is 43.44” from the tip of the nose cone and the center of pressure is 50.09” from the tip of the nose cone. According to OpenRocket, the stability margin when leaving the rail is just above 1 and does not exceed 3.2 calibers before apogee (**Figure 6** below).

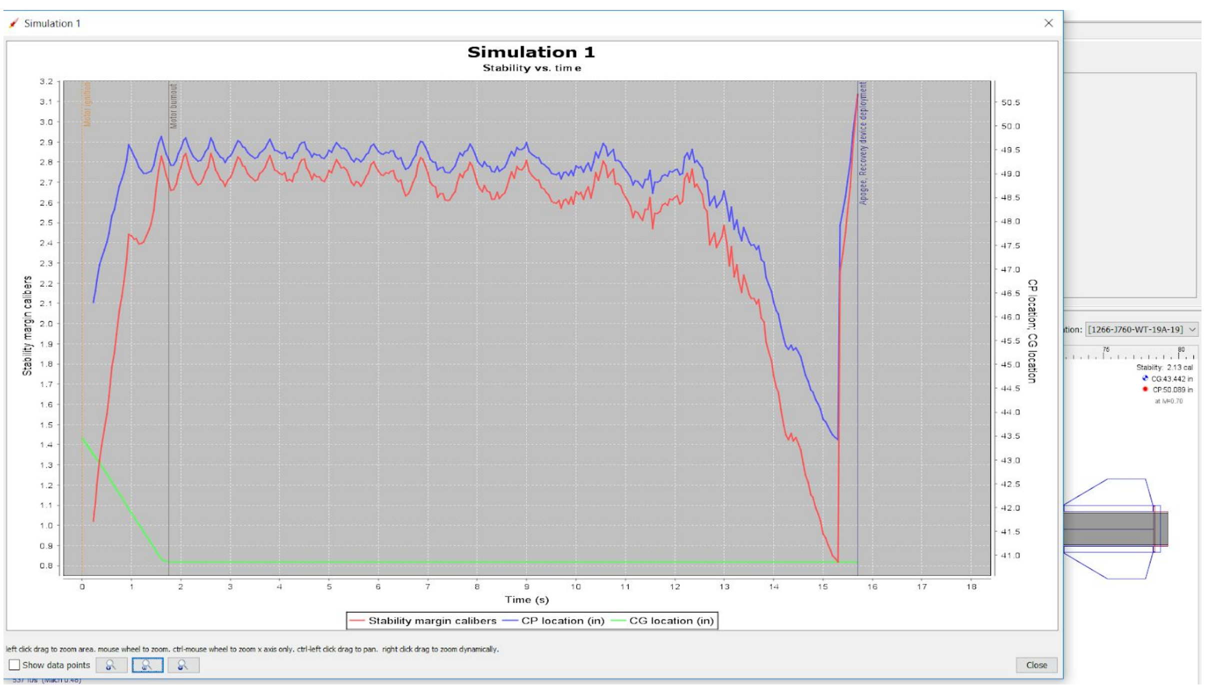

Figure 6. Stability vs Time

In order to separate the sections of the rocket in a well-timed manner, the commercial altimeter will detonate a black powder ejection charge at apogee and allow the system to descend under an 18” drogue. The Rocketman 6’ 4-line canopy main parachute will remain closed, mechanically constrained by the Jolly Logic Chute Release. Should the commercial altimeter fail, the motor ejection charge will serve as a backup drogue deployment method. As mentioned previously, the Jolly Logic Chute Release system will then mechanically deploy the main parachute at 700 feet in altitude. The parachutes will be attached to 30’ of tubular nylon shock cord secured to the motor mount using a forged eye bolt. All such hardware will be at least ¼” stainless steel.

3. Avionics Systems

3.1. Commercial Altimeter

A StratoLoggerCF will be used as the rocket’s commercial altimeter. It will record the rockets peak altitude and maximum velocity after flight as well as take 20 samples of altitude, temperature, and battery voltage per second. The information can be downloaded to a computer with a DT4U USB interface. The StratoLoggerCF will serve as the primary means of parachute deployment and will deploy the free drogue and the constrained main parachute at apogee.

3.2. Noncommercial Package

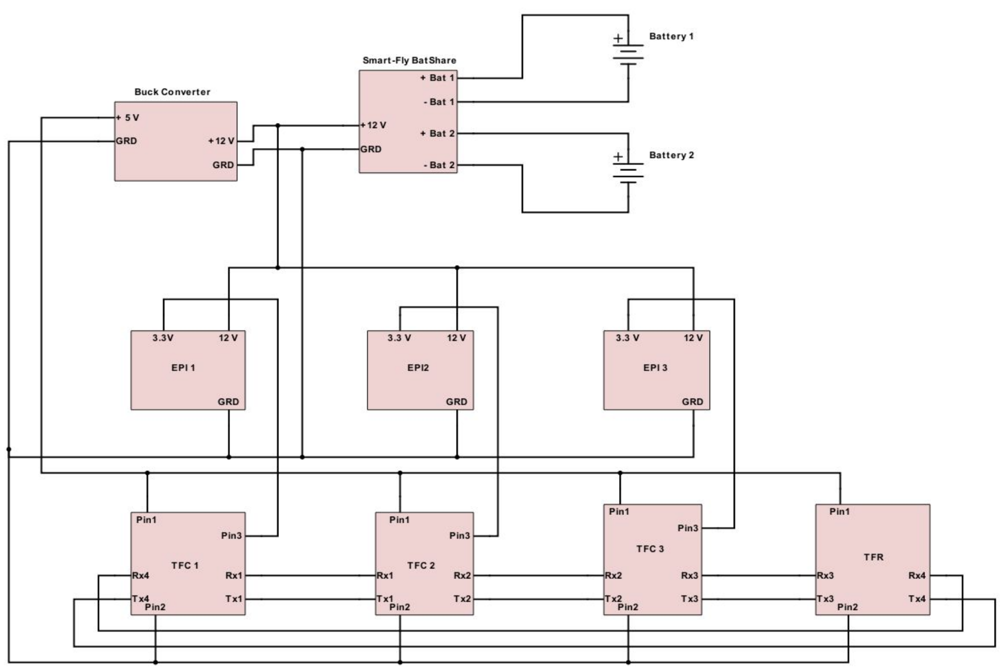

Figure 7. Noncommercial Avionics Block Diagram

3.2.a. Teensy Flight Controllers (TFCs)

Aquila II uses three separate but identical Teensy 3.6 Flight Controllers (TFCs) to read information from the IMUs. Each controller will work both independently and together with each other. Each TFC will have its own IMU and will read data from the IMU and send it the other two TFCs. Once the prioritized TFC has received data from the other two TFCs, it will average the IMU readings from all three IMUs. Then it will process this data though its control algorithm, opening or closing the valves necessary to adjust the rocket's roll to the desired angle. If one TFC fails then the other two TFCs will be alerted via a break in communication and will be capable of performing exactly the same tasks by assigning one of them to take over as the prioritized controller. Thus using three independent flight controllers provides redundancy to the control system and a higher accuracy from the IMU readings.

3.2.b. Teensy Flight Recorder (TFR)

A fourth Teensy 3.6 will be used as the rocket's flight recorder and as the communications computer. All flight data (the data from all three TFC IMU's, all other data received from the TFC's, and any information conveyed from the ground station) will be logged to the SD card plugged into the Micro SD card slot on the Teensy board at a rate of 10 Hz. A UART connection will be used to connect the Teensy board to an XBee communications module and provide power to the XBee, requiring a total of four pins. The Teensy will also be connected to each of the three flight controlling Teensy boards via a serial transmitting and receiving line, requiring a total of six connecting lines.

3.2.c. Inertial Measurement Units (IMUs)

Aquila II uses three Prop Shield IMUs, which have prewritten libraries designed to work specifically with the Teensy 3.6. Testing with alternative IMUs such as the L3G4200D and MPU9250 showed that their accuracy and library compatibility were not sufficient. The Prop Shield has a 6-Axis Linear Accelerometer, 3-axis linear magnetometer, 3-Axis Digital Angular Rate Gyroscope and a Precision Altitude and Temperature sensor. The three IMUs will be mounted as evenly throughout the rocket as possible to provide the maximum accuracy: one will be mounted in the nose cone; one will be mounted close to the tail of the rocket; and one will be mounted in the middle of the rocket.

3.2.d. Electronics-Pneumatics Interface (EPI)

Each of the valves will be be connected directly to the 12V power supply and will be switched on and off with a PSMN4R2-30MLDX N-channel MOSFET

(NMOS). All three TFCs will have an output pin connected to each valve NMOS gate pin; to turn a valve on, the active TFC will write 0 volts to the that NMOS gate. Diodes will be placed in between each output and its corresponding NMOS gate and pull up resistors will tie each gate to 3.3 V. These additional components will ensure that only the prioritized TFC can affect the valve switching. Finally, a flyback diode will be placed in parallel with each valve solenoid in order to prevent high voltage spikes when the valve solenoids are switched off. These circuits will be included on the PCBs mounted on the electronics sled.

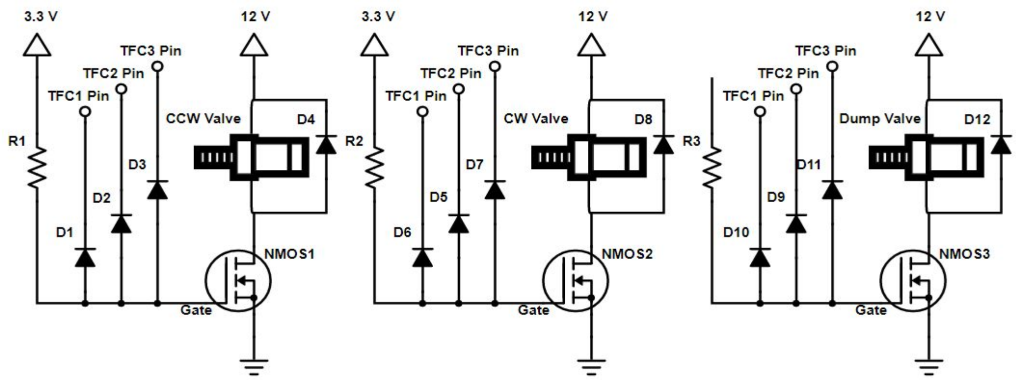

Figure 8. EPI Schematic

3.2.e. Power System

Aquila II is powered by two lithium polymer batteries. Each battery is a 3 cell providing 11.1 volts and is rated at 450mAh. Both batteries will be connected to a Smart-Fly BatShare, a commercial device that allows operation of both batteries at once but switches to a single battery if one is to fail. An eBoot Mini MP1584EN DC-DC Buck Converter is used to convert the 11.1 volts down to 5 volts to power the TFCs, TFR, and IMUs. With both batteries fully operational the power system will have a total rating of 900mAh, and if one battery fails it will drop to 450mAh. Taking into account the expected current draw, the avionics system operation time even on one battery exceeds any expected flight time and stand-by time combined.

3.2.f: Control Algorithm

The prioritized TFC will be responsible for incorporating the IMUs and EPIs in a closed-loop control algorithm. The X and Y axes magnetometer readings from all three IMUs will be taken at a frequency of 10 Hz and averaged to correct for sensor error and obtain data that is more accurate for the entire airframe. The magnetic heading will then be determined by finding the angle of the magnetic field with respect to the X and Y axes. As in a standard control loop, the sensor reading will be subtracted from the target value to calculate the error.

A control signal with a value between -100% and 100% will be generated by applying Proportional, Integral, and Derivative (PID) gains to the error. The exact values of these gains will be tuned using a simulation of the rocket built in Simulink, and it is likely that different sets of gains will be used for the separate challenges of actuating the rocket and of holding it steady. If the control signal is a less than 0, the TFC will send an inverted PWM signal to the switching MOSFET for the Clockwise Solenoid Valve (CWSV) with a frequency of 5 Hz and a duty cycle equal to the absolute value of the control signal. If the control signal is greater than 0, the TFC will send a similar signal to the switching MOSFET for the Counterclockwise Solenoid Valve (CCSV). This has the net effect of constantly creating a torque on the rocket airframe that drives the error to zero. Current simulations indicate that Aquila II will be able to complete any given roll command in under 2 seconds. A high level block diagram of the control algorithm is shown in **Figure 9.**

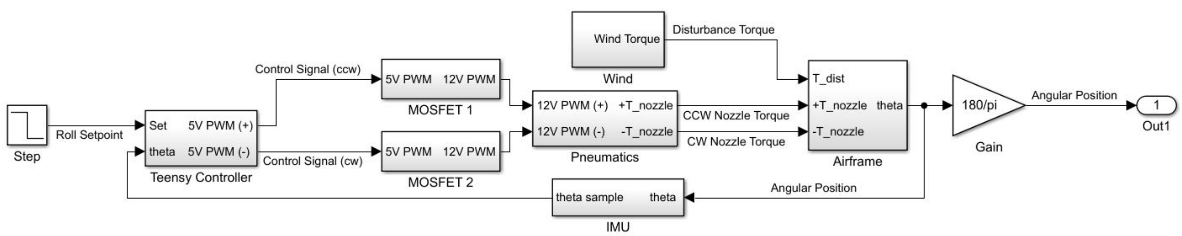

Figure 9. Control System Block Diagram

3.3. Hardware Interface

3.3.a. Avionics Bays

For the UAB, a removable sled design will allow for easy separation for maintenance of the avionics payload from the rocket even after full assembly. The shape of the UAB follows a spool like design, with two circular bulkplates connected in the center by a rectangular prism. Each face of the rectangular prism is where the microcontrollers will be mounted. The batteries will be secured on the top circle and will be shielded from temperature, pressure, and physical damage. The external switches to turn on the avionics will also be located on the top circle on opposite sides of the center prism. To connect to the electronics that are not located in the UAB, regular pin headers will connect the IMU's, and TX30 connectors will connect the solenoid valves. These connections will be secured by electrical tape during flight, but will allow for easy disassembly during the manufacturing and launch preparation stages. The electronics sled for the commercial altimeter will be 3D printed and held in place within the lower coupler by threaded rods.

3.3.b. External Switching

Three Apogee 09128 rotary switches will be used to turn power on and off; one to the valves, one to the controllers and IMUs, and one to the StratoLoggerCF commercial altimeter. The first two switches will be mounted near the top of the rectangular prism at the center of the UAB, opposite from each other and offset 90^{o} from the batteries. The third will be mounted in the LAB with the StratoLoggerCF. Each switch will be clearly labelled and externally accessible with a screwdriver through small “breathing holes” in the airframe.

3.3.c. Camera

A RunCam 2 will be used as the rocket’s camera. It has high definition recording capabilities, and will be equipped with a 64G Micro SD Card. The camera will be mounted internally above the UAB, and will be pointed at a small mirror mounted externally at 45 degrees to the surface of the rocket. This allows the camera image to be downward facing while still maintaining a clean aerodynamic profile.

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4. Pneumatics System

The pneumatics design consists of supporting equipment for the three solenoid valves. As stated previously, the CWSV applies clockwise torque, the CCSV applies counterclockwise torque, and the EDSV evacuates all gas in the system after the flight or in the event of an emergency. Feeding these valves is the propellant tank, a 30.5 cubic inch high pressure air cylinder commonly used in paintball applications. A paintball tank was chosen for its durability and reliability as paintball tanks are routinely bumped, jostled, and held in close proximity to the human body and are therefore manufactured with safety as the foremost concern. The tank will rest in a cradle of PETG plastic, that is backed by a fiberglass centering ring. The whole assembly is attached to the airframe, so the total epoxied area will be in excess of 14 square inches.

The propellant tank regulates its own output down to 850psi, but this pressure is still far too high for any of the solenoid valves or piping to be able to withstand. A high-flow inline regulator will bring the pressure down to the 100psi required by these components. The inline regulator is also a paintball accessory and will be easy to secure inside of the airframe.

After the regulator, the air tubing is forked in three separate directions: two lines feeding the roll control valves, and one line feeding the EDSV. The control valve solenoids are pulsed at 5hz and use PWM to control the total force applied. The valves are quite large, but will fit inside of the airframe with enough space for support brackets.

The outputs of the control valves are then fed into a cylindrical manifold consisting of four converging-diverging supersonic nozzles. Two nozzles will be pointed in either direction but offset 180 degrees from each other so that they will apply no net torque around the pitch or yaw axes of the rocket.

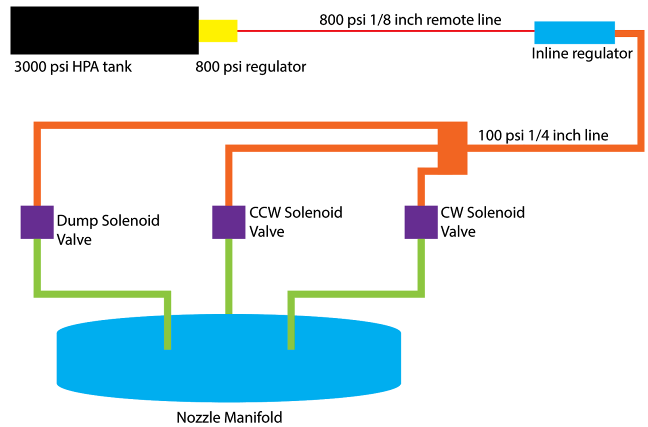

Figure 10. Pneumatics Diagram

5. Bonus Challenge

5.1. Communications System Hardware Implementation

A set of XBee Pro 60 mW U.FL Connection - Series 1 (802.15.4) radio modules will be used for communications between the ground station and the rocket. The XBee units will be paired, and interference will be limited further by the addition of a "security code" that will proceed every transmission. The TFR and ground station computer will ignore all messages not preceded by the ASCII code "A2."

The rocket's XBee transceiver will be connected to the TFR computer. The UART protocol will be used to provide power to the XBee and will act as the interface between the TFR and XBee. A wire antenna will be used with the Xbee module to provide adequate air-to-ground signal strength. The antenna will be fed through a small hole in the side of the rocket and run the length of the rocket.

The groundside XBee will use a small monopole antenna to provide its transmitting and receiving capabilities. An Arduino Uno will serve as an intermediary between the XBee module and the ground station computer.

Communication between the computer and the XBee will be done using the Uno's serial monitor. The Arduino will provide the necessary power to the XBee module, and the xbee-arduino library will be used to provide the necessary interfacing between the XBee module and Arduino Uno. Connection between the XBee and Uno will be achieved using the UART protocol. An additional wire will connect the Uno to the XBee's RSSI signal (pin 6), which will allow the ground station to monitor the rocket's broadcasting signal strength using a PWM signal. Because the Arduino Uno outputs digital signals using a 5 volt based digital logic system and the XBee module uses a 3.3 voltage based digital logic system, the connections between the Uno and Xbee will be routed through a logic level converter to ensure that all signals are using the proper voltage.

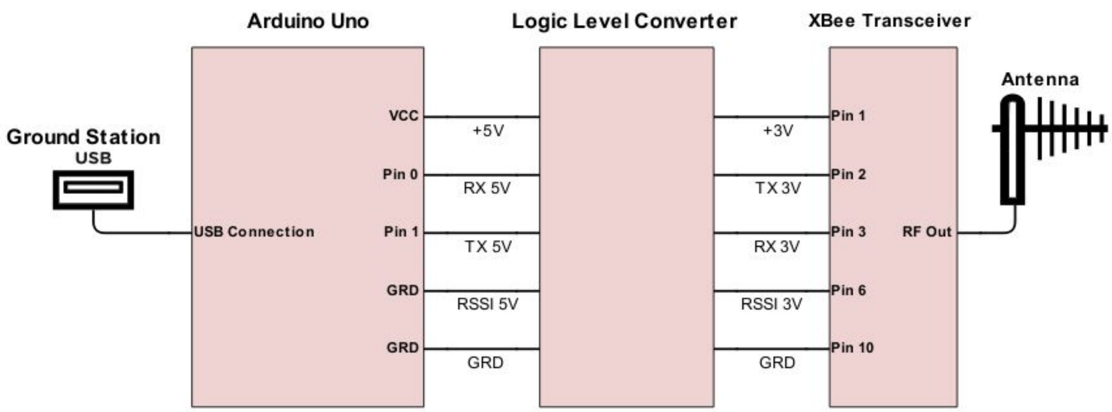

Figure 11. Communications System

5.2. Bonus Challenge Specifications

The rocket will accept an alternative set of roll commands only while on the ground before launch. All commands received must be transmitted from the rocket back to the ground station. The ground station will then send a confirmation signal back to the rocket stating that all commands are correct. Only then will the rocket accept and change its pre-programmed flight orientation program. The TFR computer will also be capable of performing simple mathematical operations which are received as commands from the ground station during flight. Aquila II's evaluated answers will be transmitted back to the ground as the last item in the comma-separated field of flight data from the rocket.

All available in-flight data will be transmitted from the rocket to the ground control station as a set of comma-separated fields at 10 Hz, including the time since engine ignition, TFC status, altitude, orientation, temperature, gyroscopic data, acceleration rate, estimated remaining tank psi, and answers to mathematical commands received from the ground station as specified in the rules for bonus challenge C.

6. Budget

Table 1: Expenses

Budget Item	Price
Noncommercial Avionics Components	$425
Commercial Altimeter	$55
Fiberglass Airframe Components	$370
Recovery Components	In Stock
Pneumatics Components	$350
Competition Registration	$400
Hotel Rooms for Launch Team	$500
Transportation for Launch Teams	$1670
Total	**$4270**

Table 2: Funding Sources

Source	Amount
Tennessee Space Grant Consortium	$1500
TTU Chapter 606 Grants	$3050
Team Dues	$200
Total	**$4750**

7. Appendix

7.1. List of Figures

7.2. List of Acronyms

- **CCSV** = Counterclockwise Solenoid Valve
- **CWSV** = Clockwise Solenoid Valve
- **EDSV** = Emergency Dump Solenoid Valve
- **EPI** = Electronics-Pneumatics Interface
- **IMU** = Inertial Measurement Unit
- **LAS** = Lower Avionics Sled
- **PID** = Proportional-Integral-Derivative
- **PWM** = Pulse Width Modulation
- **RSO** = Range Safety Officer
- **TFC** = Teensy Flight Controller
- **TFR** = Teensy Flight Recorder
- **UAS** = Upper Avionics Sled