Rocket Launched Autonomous Quadcopter Final Report

Oklahoma State University Rocket Squad

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I. Acronyms and Definitions

$3D$	Three Dimensional
$3DR$	3D Robotics
AGL	Above Ground Level
AWG	American Wire Gauge
$CapEx$	Capstone Experiment
CNC	Computer Numeric Control
$COTS$	Commercial-Off-The-Shelf
DOE	Department of Energy
DML	Design and Manufacturing Laboratory
$ematch$	Electronic Match
ESC	Electronic Speed Controller
fps	Frames per Second
ft	feet
g	grams
$GPIO$	General-Purpose Input/Output
GPS	Global Positioning System
HPR	High-Powered Rocketry
ID	Inner Diameter
$ITAR$	International Traffic in Arms Regulations
JFK	John F. Kennedy
lbs	Pounds
mm	millimeters
mph	Miles Per Hour
NED	North East Down
OD	Outer Diameter
OSU	Oklahoma State University
PDR	Preliminary Design Review
PID	Proportional-Integral-Derivative
PLA	Polylactic Acid
PSI	Pounds per Square Inch
PVC	Polyvinyl Chloride
SLA	Stereolithography Apparatus
SOP	Standard Operating Procedure
$SRAD$	Student Researched and Developed
$UAFS$	Unmanned Aerial Flight Station
UAV	Unmanned Aerial Vehicle
V	Volts
XL	Extra Large

II. Introduction

The goal of this project was to design and develop a rocket that could get a payload golf ball to at least 8,000' AGL and then return it as close to the X on the ground as possible. In order to achieve this goal, we decided to design an integrated deployable quadcopter UAV that would deploy at apogee and then autonomously fly itself back to the designated target location. This concept has never been achieved before and therefore we wanted to be the first to successfully complete the mission. Despite our work and determination we were unsuccessful of a true recovery however we believe we have made the most progress and had the most success of anyone attempting such a feat at the high-powered rocketry level.

III. Structures

A. General Design

The most unusual feature of our rockets is the location of the drogue and main parachutes. Ordinarily the main parachute goes in the forward section and the drogue in the aft portion of the rocket. However, because we chose to deploy our quad (which made up the nosecone) at apogee, the drogue parachute would deploy during the same ejection event and therefore located in the forward section.

The 5" diameter was chosen because based on simulations, 6" would become too heavy and create too much drag with commercial fiberglass to reach the 8000' altitude mark. The DOE rocket was simulated and even with an L1500T (highest impulse 98mm L-class motor), it would barely scrape 8000' without any payload. While our custom tubes ended up being lighter, we didn't know that at the time, and we felt that a 5" diameter rocket was a good compromise of lighter than a 6", but offering more payload diameter than a 4".

B. DOE Rocket Project

At the start of our semester, Dr. Jacob introduced a second project we would work in parallel with our Argonia Cup design. This was a project sponsored by the DOE (we refer to this as "the DOE rocket"), and Tim Navickas (tnavickas@kcp.com) was our point of contact there. They wanted to fly a 6" diameter by 18" long payload for testing accelerational G-forces on payloads.

On Black Friday in 2017, Dr. Jacob bought a 6" Mad Dog kit from Madcow. The forward section would hold the payload and no part of that section would separate. The drogue charge would fire at apogee, and the main would be released via Jolly Logic at a lower altitude. A PowerPoint presentation Lucas compiled is saved in the DOE Project folder along with the OpenRocket model.

At the end of February, Tim contacted Lucas to let him know he couldn't get the payload approved from their end, so they wouldn't be needing the flight this semester. He would like to fly it at Airfest or in October, and Lucas has forwarded that email thread to Austin Stottlemyre, the Rocketry Team Director at the time of this writing.

If over summer 2018, Tim has everything ready for Airfest, the DOE rocket may be built in 2 weeks' time or the Spaceport America Cup rocket used.

Several items purchased at the very beginning of the semester were intended for use with the DOE Rocket including the Cert-3 XL (orange and yellow) parachute, an extra 98mm flanged motor retainer, and the blue 1" nylon shock cord.

C. Structures Introduction

The Structures Team consisted of Mechanical Engineering majors Chad Kenkel and Gerald McCullers, and Aerospace Engineering major Lucas Utley. Gerald also served as the OSU AIAA Rocketry Team's Structures team lead. There were parallels in what our capstone team did and that benefitting the rocketry team. As the rocketry team had never made fiberglass components before, the work from our capstone team would help the rocketry team in their endeavors.

1. Rationale for Making SRAD Fiberglass Parts

From the beginning, we chose to learn and make suitable fiberglass tubes and sheets rather than purchasing them commercially due to the high cost of commercial composites (tubes from Wildman or Madcow Rocketry, and sheets from McMaster-Carr, Garolite G-10). Chad was the only one who had any prior experience in working with fiberglass from scratch. He was part of the OSU Sailing Club, and the repairs he made gave him some exposure to using fiberglass cloth and resin.

We expected to be making 5" diameter tubes, and commercial 5" tubes from Madcow Rocketry cost $34/foot and may only be purchased in 30" or 60" sections with high shipping costs for over-sized parts. Wildman Rocketry is $36/foot for 5" tubes, and has more options in 1, 2, 4, and 5-foot sections, but this would still be costly. We expected to build at least two versions of the final rocket, and being dependent upon suppliers, inevitable delays, possible out-of-stock issues, and shipping times, we didn't want to be constrained that way.

To make our own tubes, we would need practice making them, finishing them, and evaluating their compressive and hoop strengths. Compressive strength is necessary for supporting the weights of any rocket parts above that tube, and hoop stress is vital during ejection charge internal pressurization.

Finally, the ability to make our own tubes would allow us to have a finished product within a day rather than waiting a week or more for commercial tubes to arrive in the mail.

2. Initial testing of SRAD Fiberglass Parts

We began making tubes using 2" PVC as the mandrel. These small-scale tubes allowed us to do many iterations without using much material. The smaller size also allowed the whole mandrel to be handled easily. These tests served mostly to develop layup methods, mold release systems, and determine a rough estimate of the number of layers needed to achieve the necessary strength and rigidity. Finding a method that allowed us to remove the finished fiberglass tube proved to be the most difficult part and one of the few things that didn't necessarily scale as we predicted when we moved up to larger-diameter tubes.

Initially we only used wax paper in between the mandrel and fiberglass. This did not slip off the mandrel smoothly as we had hoped, and we ended up using dry ice to shrink the PVC enough to allow the fiberglass tube to be slipped off. We then began using lubricant in between the mandrel and the wax paper to help slide off the mandrel. Cooking oil was used as lubricant at this stage. For these small diameter tubes, this method allowed the tubes to slide off the mandrel with ease. We determined that at this small of a diameter, tubes with as few as 3 layers were still very strong and rigid. These tubes we were making were also consistently lighter than commercially available tubes, something we hadn't been counting on.

To test the scalability of this method, we began testing with 4.5" OD tubes using 4" PVC purchased from Lowe's. One layer of wax paper was used to separate the tube from the mandrel with a coating of cooking spray on the mandrel underneath the wax paper and another coat of spray on the outside of the wax paper. These tubes proved to be harder to remove than the smaller versions and a t post driver method had to be adopted to remove one iteration. It was determined that 6 wraps of fiberglass still provided plenty of rigidity at this diameter while retaining weight savings. These tubes went on to become *Everything Is Sticky.*

Figure 1. Chad with our t-post driving system

3. Everything Is Sticky

A month into the semester, the Kloudbuster's February launch was to take place before we could have anything ready to test or fly. However, due to bad weather it was delayed a week, and this posed a unique opportunity to quickly build a rocket completely from scratch in 10 days using our own fiberglass parts. While we couldn't simulate the compressive strength expected in the final competition flight, it would give us practice making our own airframes, motor mount tubes, and sheets to become fins and centering rings. It would also verify that these parts could withstand the basic stresses experienced in flight from motor boost, ejection charge separation at apogee, parachute deployment, and touchdown. We expected the longest section in the final iteration of the rocket to be 40", so that was the airframe section length to be used in this test flight.

Using the 4" PVC mandrel, we built the airframe around that using the cloth Chad had available from the sailing club. Due to the adhesive and cumbersome nature of curing fiberglass resin, much of Chad's garage became sticky, as well as our clothes, skin, phone cases, and shoe soles. This became the origin of the name, Everything Is Sticky.

The nosecone was 3D printed from PLA plastic and carried a PerfectFlite ARPA altimeter. It would be dimensioned as the final quad/rocket nosecone would be. We built the 38mm motor mount tube from a long 38mm motor casing. The first attempt didn't use lubrication and had to be chiseled off to release it from the motor casing. The second iteration went just fine thanks to a generous coating of petroleum jelly directly onto the motor casing exterior and then wax paper and cooking spray as normal. 2 centering rings were CNC cut from a fiberglass sheet consisting of 8 layers of fiberglass cloth. 3 fins were cut from another sheet, also from 8 layers. It resulted in a sheet 0.15" thick, which is approximately close to commercial kits of this size.

All parts were assembled with RocketPoxy as purchased by Dr. Jacob. Motor retention used threaded inserts epoxied in and bolts with washers to hold the motor in place. Rail buttons were left over from the rocketry team and used here.

On February 17th, 2018 Everything Is Sticky flew on an I357T that belonged to the rocketry team. It reached approximately 160' and suffered no damage whatsoever, not even to the printed nosecone. This was our green light to proceed with more ambitious fiberglass work in making larger tubes and a larger rocket.

Figure 2. Chad, Gerald, and Lucas with *Everything is Sticky* on the Pad

D. Scaling Up and Verifying Our Tubes

Obtaining a suitable 5" casting mandrel was significantly more difficult than expected. Public Missiles is generally a great source for purchasing phenolic airframes and coupler sections of various lengths, but they do not carry 5" sections. Scouring every website listed in the back of *Modern High-Power Rocketry 2* by Mark Canepa was unsuccessful as well in obtaining a tube that has an OD of 5". PVC wasn't an option because it measures tubes with respect to the ID, and as they are a quarter inch thick, even a 5" PVC pipe would have an OD (and therefore casted tube ID) of 5.5" or more. Custom PVC wasn't an option.

Next were cardboard mailing tubes. Plenty of suitable options existed here in terms of dimensions, but all distributors only mail cases of 7 or more tubes at once for a package of $75. Shipping such a large container would have added another $70 or more. Not feasible, as we only needed one such tube to begin with.

The tube (or rather, pipe) that worked was a vacuum-rated steel pipe from McMaster-Carr. It was $50, could be purchased individually, had a 5" OD, and was 60" long. Although the website said delivery time could be 2-3 weeks, it arrived within 3 days. While cumbersome and heavy, it served us well in making over a half-dozen tubes.

1. *Compression Testing*

To verify that our tubes would withstand the stresses of launch we decided compression testing was necessary. We inquired about using a facility on campus, but the campus facility could only test lengths up to 20 inches and our inquiries about using this facility were not well received. We also needed to test full length sections as buckling was of significant concern. To do this we were able to use Chad's dad's squat rack with a board atop the tube to spread the load of the bar evenly across the cross section of the tube. The squat rack had safety bars that could be placed at three-inch intervals. This allowed safety bars to be placed an inch below the bar when the bar was resting on the top of the test section. This ensured that if the tube did fail catastrophically the weights would only fall the one inch to the safety bars instead of all the way to the floor. Collars were used on the bar to prevent weights from being able to fall off the bar if the bar did drop to the safety bars.

The highest compressive load we could achieve with the bar and weights was 310 lbs. A 40" long 4.5" ID section with 3 wraps that Gerald made days beforehand as a demo with the rocketry team structures members was tested first. This section was very flimsy and could be flexed by hand. This section withstood 310 lbs with only minimal flex, much to our surprise. Determined to create catastrophic failure, this section was destroyed by structures team members with a rubber baseball bat. The second section tested was a 5" ID section 40" in length made with 6 layers. This section withstood 310 lbs with no flex. To increase the load, Lucas hung from the chin up bar on the squat rack and lowered his weight onto the bar increasing the load to 475 lbs of compression load. The section showed no damage whatsoever. This tube became the aft section of *Everything Is Slippery.*

Figure 3. Compression Testing

2. Everything Is Slippery

Everything Is Slippery was built for our first full-scale test flight and would later serve as our backup rocket in the competition. It remained unpainted which helped a great deal during ejection charge testing and inserting shear pins. It was named from extensive lubrication that made our hands and shoe soles very slick.

The aft section of the rocket was the tube used in compression testing as described above. This batch of tubes weighed exactly *half* of what a commercial tube of the same lengths and diameters would be. A commercial section 40" long was calculated to weigh 66 ounces, but our 40" section weighed in at 33 ounces. This was a pleasant surprise to know that not only were these tubes adequately strong, but it came at a significant weight savings.

The motor mount assembly contained a 15" long 98mm motor mount tube (cast from a 98/10240 casing) and 3 centering rings. Only two centering rings were epoxied on initially. The aft section was then slotted using the team's fin slotting jig and motor mount assembly epoxied in. The fin tab on each fin spanned the entire fin length.

Due to the new 98mm flanged Aeropack retainer, there was some concern about the aft-most centering ring take the brute force of the motor's thrust. To help with this, small 0.5"x1" fiberglass segments were epoxied against the fin. This way, the centering ring had something to sit on rather than relying solely on the epoxy joint. Once each fin was affixed, the aft centering ring was epoxied in place, with it being flush with the end of the motor mount tube as is necessary for the flanged retainer. The retainer holes were drilled and threaded, and the retainer was affixed. However, only 9 of the 12 threaded holes lined up with the machine screw. RocketPoxy was used throughout.

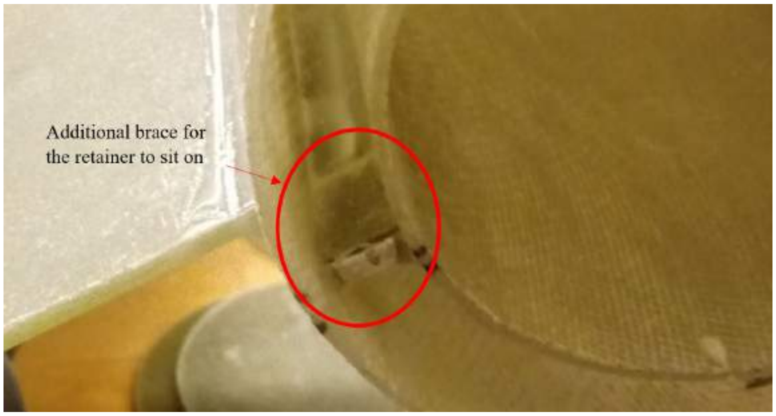


Figure 4. Additional Brace for Retainer

This rocket was used for extensive ejection charge testing. We were aiming to use a piston to push out the quad and drogue parachute, but complications with this prior to the March launch abandoned the piston for that flight. We had problems with the piston moving part-way through the tube but then getting "sucked" back towards its original position. This was observable by slow-motion video during these tests.

Figure 5. Rail button secured via wood screw, plywood square, and epoxy

The altimeter bay and recovery systems were handled by the structures team. The coupler was cast from a 3D printed mandrel, and while uneven, still performed well. It was only 9" long, shorter than it should be. Couplers should be one body diameter on each interfaced side plus the slip band length. For a 1" slipband, the couplers for a 5" rocket should be 11" long. The reason this one was shorter was because the 3D printed mandrel frayed at one end and wasn't long enough due to a print failure. The bulkplates were CNC cut to contain a coupler bulkplate secured to an airframe bulkplate.

On *Everything Is Slippery*, a 3D-printed sled was used that contained attachment points for two rotary switches. The PLA plastic allowed for holes to be tapped with ease and held up throughout its one flight and countless ejection charge tests.

The primary altimeter was a Missile Works RRC3 Sport Altimeter purchased by Dr. Jacob, and the secondary was a PerfectFlite StratologgerCF, borrowed from the rocketry team. Main was set to deploy at 1000ft and Dr. Jacob's radio tracker was zip tied to a threaded rod inside for tracking. For mounting the batteries, 9V battery holders were purchased from Missile Works and epoxied onto the sled. Wires were soldered on and connected the batteries and switches to the altimeters.

The arming switch is the most vital design feature of an altimeter bay and its altimeter sled. Two primary methods exist with rotary switches (purchased from Missile Works): an internally mounted switch fastened to the sled itself or externally mounted switch that is fastened to the slipband part of the altimeter bay. They each have pros and cons.

An internally-mounted switch (as done in *Everything Is Slippery*) makes the sled one complete part that may be removed entirely before and after flight. While that element is convenient, it means that a small screwdriver must be carefully inserted into a static port hole to turn and arm the switch. Usually the screwdriver with a large enough flathead to arm the switch is far larger than the appropriately sized static port hole. You risk inaccurate readings if the static port hole is improperly sized. Even if the screwdriver is small enough, a large hole is needed to accommodate the USB-altimeter connection cable required when ejection charge testing with an RRC3 or StratologgerCF. Another drawback to this switch mounting method is that the switch must be very carefully aligned with the static port hole to ensure the screwdriver gets inserted properly to arm the switch. Especially with more than one switch, this alignment can be very difficult to get right. We do not recommend this method of mounting switches.

The other method to mount switches is to affix it to the altimeter bay's slipband. It can be done with a ” hole all the way through, or the switches can be made flush with the airframe by drilling a ” hole in the coupler, and a ” hole in the slipband. This makes a countersunk hole and is better for aerodynamics. These holes must be carefully aligned and drilled before epoxying the slipband to the coupler. You can then use the rotary switch's included nut to tighten the switch to the altimeter bay. Additionally, if two switches are being used, one switch may be removed to expose the hole which is sufficiently large enough to insert the USB-altimeter cable, and the other installed switch can be used to turn the appropriate altimeter on and off. The drawback to this method is that the switch must have long wires soldered to it, so that the sled may be pulled out of the coupler when doing work on the sled. While the long wire lengths may be a bit cumbersome, it is preferred over the first method explained in the previous paragraph. This type of altimeter bay was used in *The Other Things* as explained later.

Other miscellaneous information on the altimeter bay includes using 5/16” zinc-plated eyebolts (for corrosion resistance from black powder and rust forming), basic terminal blocks from Missile Works, and 3D-printed ejection charge canisters. The canisters featured a notch in the top that the ematch could insert into to make the top flush. This aids with preventing black powder leakage when using model rocket wadding and masking tape to hold the black powder securely in the canister. The terminal blocks and ejection charge canisters were affixed with a 4-40 screw with tapped holes. At the time of writing, this tap and bit are housed in the clear plastic drawer labeled ”Ebay Mounting.” These screws were also used with neoprene washers to mount the altimeters. The neoprene washers were useful because they absorb vibrations in flight.

Finally, the launch of *Everything Is Slippery* occurred on March 11, 2018 in Argonia, KS. The rocket launched within the last half hour of the launch window because of delays with the quad, and its own black powder charge. For some unknown reason, the quad became very tight when inserted into the top airframe. Fearing it would be stuck, it was only inserted partway into the airframe on the launchpad without shear pins.

The ”up part” of the launch went without a hitch, but we believe the quad got pulled deeper into the upper airframe because there was no separation at apogee. The rocket returned ballistically with eyes on it the whole way. The main did deploy at 1000 feet and caught the rocket, flinging the quad away in the process. Upon recovery, the rocket was in flawless condition having no damage from the main deploy at high speed. It reached an average altitude of 10,222 feet, with the altimeters only 20 feet apart in altitude reading.

While the unsuccessful quad wasn't the preferred outcome, it did verify our fiberglass parts for flight. We could proceed without that as a concern.

Figure 6. Lucas awating flight-ready status of *Everything is Slippery*

E. Final Structures Testing

1. Lubrication Issues

Following the flight of *Everything Is Slippery*, we began the second and final iteration of the rocket that would be used in competition. There were two schools of thought on which rocket should be used for the actual Argonia Cup. *Everything Is Slippery* was flight-proven and held up just fine. However, the rushed assembly and jerk of main deployment at high speed was of concern. It was decided the next rocket would be made nearly identical, but with more time to build it with epoxy, it would likely be stronger and be used for the competition. The forward section was also elongated by 6” to allow extra room for the quad, drogue, shock cord, and piston. With a proper 3D-printed mandrel, the altimeter bay coupler was also longer.

To begin making the tubes for this next rocket we followed the same procedures as before. The first of these tubes was left on the mandrel for 5 days because we got busy. Chad and Lucas were unable to pull it off, even after building a harness between two trees to better pull. By heating it with a heat gun, the fiberglass softened, and we were able to use a screwdriver to chisel through the fiberglass to extract it from the mandrel. We figured the difficulty of this tube was due to it sitting for 5 days. We tried again after spring break and only let the tube sit overnight before trying to the pull the tube off the next morning. This came at no avail also. Even with the help of Speedfest people at the DML, we managed to pull it to the edge of the pipe (about 5” of travel down the pipe), but no further. At the opposite end of the tube, Lucas and Ben drilled holes to insert a ” OD steel rod to create t-post driver like we had done before with the PVC pipes. By slamming it on the ground, we got it to move another ” off the pipe, but the holes in the steel pipe sheared through and the steel rod got very bent. As a last-ditch effort, Lucas filled the pipe with ice as a vain attempt to constrict the pipe enough to pull off the tube. This was also futile. We heated and chiseled the tube off.

As a third attempt, we thoroughly cleaned the pipe with mineral spirits and used extra petroleum jelly. We waited less than an hour before trying to pull it off. Cut to 3 hours later and using an F350 diesel truck to pull the pipe from a telephone pole harness, paracord snapped and fiberglass sheared through. We heated and chiseled off the third straight tube.

We met at the DML the following afternoon to speak with the Speedfest faculty members to see about using a wax and release system. While we tried to find Dr. Arena, we asked ourselves why we didn't just add a second wrap of wax paper like Gerald did with the structures team when making their fiberglass tubes for their Argonia Cup rocket. We left the DML and tried it right away. The wax paper bunched up a bit with creases, but after 45 minutes, Gerald and Lucas pulled off the tube with bare hands and no effort. Problem solved. We went on to perfect the wax paper wraps to minimize the imperfections.

On the failed tubes, we think that the further the tube got pulled down the length of the pipe, the friction increased making it *more* difficult to extract, contrary to what we thought. We noticed after chiseling off the pipes that any exposed wax paper did not pull down the pipe length, even by itself. With those lubrication issues behind us, we were on the fast track to building *The Other Things*.

2. Ejection Charge Testing

Throughout the semester, extensive ejection charge testing was done. This 5" diameter airframe was the largest anyone from our team had worked with, and deploying the quad ended up being a tricky solution that didn't come easily. As part of Jake's, Nick's, and Lucas' CapEx work for MAE-4223, we opted to use a piston-cylinder ejection system. This seemed like a good idea because the piston would push out the quad and drogue parachute in one go. This didn't work out nearly this easily. CapEx testing ended up slipping to the day *after* the Argonia Cup because we'd already learned enough through our own testing that the CapEx was more about the grade than real meaningful data to benefit the capstone progress.

The first test took place with *Everything Is Sticky* just before the February launch. This was a no-brainer because it only contained a parachute and the nosecone and nosecone coupler were 3D printed, but it validated that the tubes were sealed and wouldn't rupture due to internal pressure.

The next series of tests occurred just before the March launch when we found out that using a piston wasn't nearly as trivial as we were expecting. Because our fiberglass tubes were translucent, we were able to view the piston behavior using slow-motion video. The piston would travel a short distance upon firing, but then get sucked backwards to or close to its starting position inside the tube. The quad was released, but not the drogue parachute. After online research, and in the interest of time, the piston was abandoned for this launch and the drogue parachute instead sandwiched between the 3D printed motor mounts of the quad arms. This was successful, and the quad was ejected while also released the drogue into the air. This would not work for the actual flight with the quad props but making the piston work would come later.

Following the March launch during spring break, several members for all the teams sought to get the piston ejection system working. By experimenting with spacing and a vent hole, it was successful in deploying the quad analog and the drogue. This didn't work especially well, but it functioned nonetheless. We aren't exactly sure what the root cause was but having more space in the black powder compartment helped as well as a vent hole in that section.

The day before the Argonia Cup was the final round of ejection charge tests. Little had changed about the design from *Everything Is Slippery* in this regard except the piston was of better quality and the section was 6" longer. The first series of tests were successful in ejecting the quad, but not the drogue. A vent hole was forgotten, but even after that was drilled in the appropriate section, the drogue would only make it to the edge of the airframe. The main parachute was also having difficulty coming out, but we learned that tying it closer to the plane of ejection helped. See additional comments section later in the paper.

At 1:00 AM the night before the cup, we decided the tests were good enough, partly also because we sheared through the rivets holding the PLA quad bases together. While we talked about how to fix that problem, Lucas had the sudden idea to take advantage of using redundant altimeters. The primary altimeter (the RRC3) could fire at apogee like normal to eject the quad. Then, the secondary altimeter (the StratologgerCF) would use a programmed apogee delay of 3 seconds to fire a second charge to eject the drogue parachute all the way. At 2:00 AM, Gerald and Lucas tested this with great success. A second 3D-printed ejection charge cap was installed, so rather than having two electric matches feeding into one ejection charge canister, each match fed into its own black powder charge. Had this been thought of the month before, it would have eliminated almost all the ejection tests we ended up doing because so many of the difficulties arose from ejecting the quad and the drogue parachute.

General comments on ejection charge testing are in this paragraph. These tests aren't loud. You could get it approved to be done at the DML, as our CapEx Project involved ejection charge testing, and we did it at the DML. See our SOP in the Aerolab folder from the Google Drive. We imagine there would have to a DML staff member present however which could limit your tests because we did a lot of ours at Lucas' backyard on weekends or at dusk. The PerfectFlite DataCap software in junction with a StratologgerCF altimeter and USB interface were used to connect for the firings. A wireless mouse was used as a launch trigger by hovering over the "Fire" button, then backing away and clicking when ready.

The parts will smell bad from the gunpowder after each firing, so let it vent and clean before taking inside buildings again. Be mindful of the fin orientation; while it never happened, a possible weak fin could break if it is facing into the ground and gets plowed into soil from the rocket falling off the stand as is normal in such a test.

In the process of getting the piston to work, we tried an initial test with just the piston, no shock cord, quad, or chute, and found its horizontal distance traveled (it is like a cannon). With the given height, it was calculated that the piston left the tube around 110mph.

3. Dress Rehearsals

This was an idea proposed by Lucas to help with pre-launch procedures on the field the day of a launch. It was suggested because many members of this capstone team were also involved with preparations for the rocketry team. The rocketry team was flying their own Argonia Cup rocket as well as the 2018 Spaceport America Cup rocket, a 12' tall vehicle flying on an M1500G to verify that it would hold up structurally.

To ensure no team member overlap, a dress rehearsal was done on Wednesday, April 4th with both groups preparing their respective rockets just like they would the day of the launch to make sure no team members were needed by both groups at the same time. We brought out the launch pad in front of the DML and the rocketry team filled out a flight card, the works. Except for the rocket motor, electric matches, and black powder, everything was done like a real launch, even down to arming the quad and arming the electronics. A wire short was inserted for an ematch so that even the altimeters would read continuity. While this was good practice, numerous delays on the recovery side of things kept these processes from going well for the rocketry team.

The benefits of such a dress rehearsal is to ensure the rocket is nearly complete days before the launch, and it addresses issues such as an altimeter switch being covered by the rail or needing to bring a ladder to arm tall switches. It allows you to realize problems you may not notice or be aware of when the rocket is horizontal or in many pieces. Had we and the rocketry team had had the Spaceport America Cup rocket ready at the time and included it in the dress rehearsal, we would have noticed how loose some of the couplers were and been able to fix it before going to Argonia. Fortunately, this issue was resolved on the field in an hour, but other problems may not be as forgiving.

F. *The Other Things*

The Other Things was the rocket used in competition for the Argonia Cup. The name was inspired by JFKs moon speech. The quad was named *The Eagle* to pair with the rocket.

The biggest differences as mentioned before included an elongated forward section, an upgraded altimeter bay, better fin fillets, and a vinyl wrap courtesy of Jake Rosario.

The elongated section was made 6" longer to allow a looser fit of the drogue recovery, since we noticed that more room in the piston compartment benefited the ejection capability of the piston.

The upgraded altimeter bay used a longer coupler and a thicker slipband. It featured countersunk switch holes which sat flush against the airframe. The sled was a simple rectangle of " plywood with certain 3D-printed parts glued on with 5-minute epoxy. The 3D-printed affixed parts included mounts for the threaded rods and rectangles to provide added support for the battery holders. The threaded rods were not attached to one side, either. By putting one rod on one side of the sled, it kept more of the sled in-axis through the rocket. Originally, another 3D-printed sled was going to be used, but support material can affect the smoothness of a plate, and the sled was so simple that Lucas felt it would be simpler to print the attachments and then epoxy those onto a section of plywood. Wood is less susceptible to warping in heat as well should the launch day be hot and the rocket sitting on the pad for a long period of time.

A new piston was also used. By using 5 wraps of fiberglass around the coupler mandrel, it created a good seal while still sliding smoothly through the tube with minimal sanding. Because of a new drogue recovery layout, this piston featured an eyebolt facing each direction as attachment points.

The new drogue recovery layout went as follows from bottom (forward altimeter bulkplate plane) to top (quad, nosecone): altimeter bay bulkplate, short 4" length of shock cord with Nomex, piston, long drogue parachute shock cord, drogue parachute tied to the very end of the shock cord, quad motors and arms, and quad. The first ejection charge pushed out the quad, then the second charge pushed the piston out the rocket which meant the drogue was outside the rocket also.

Because this rocket wasn't as rushed as *Everything Is Slippery*, improved fin fillets were used. After the aft airframe was slotted and the fins sanded, the fin tab was covered in epoxy, but the majority of the epoxy went into the slot and allowed to dribble onto the 98mm motor mount tube. The fin was inserted and kept upright as best as possible. As the RocketPoxy stiffened and cured, a wood dowel was soaked in isopropyl alcohol and inserted between the motor mount tube and airframe and pushed the epoxy back up onto the fin. The bond between the fin and motor mount is the most important, so it was critical that as much epoxy was on that joint as possible rather than sliding down around the motor mount tube. Minimal epoxy was left to cure outside the airframe.

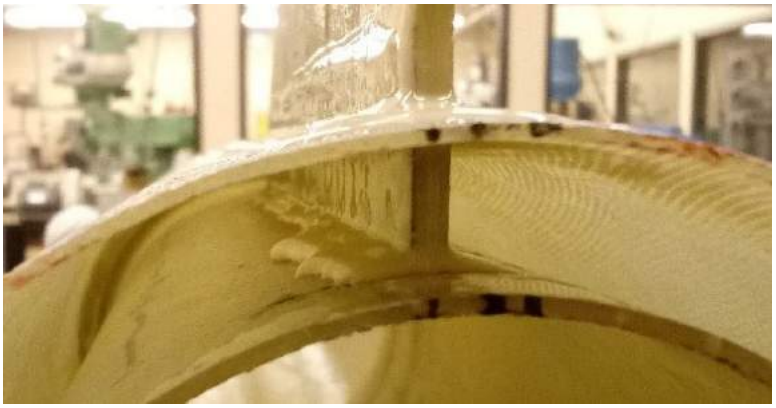


Figure 7. Epoxy running down motor mount tube without dowel assist

Once that first round of epoxy had cured, the next two fins could be attached in the same manner, one at a time. Once all three were finished, the exterior fillets were made. With one fin pointed downwards, two channels were made that allowed the epoxy to fill in nicely. Black epoxy pigment was used for aesthetic purposes. A tongue depressor popsicle stick wetted with alcohol keeps the epoxy from sticking to the stick as badly and the sticks' rounded radius is good for fillets. This process (may) be stronger but takes twice as long because it is as though you are epoxying on twice as many fins.

Figure 8. Getting *The Other Things* ready on the pad

G. *If You're Reading This, It's Over*

The idea for this rocket was conceived 5 days before the Argonia Cup. It went from proposal through design, assembly, ejection charge testing, to test flight within 50 hours. It was built to be a last-ditch final effort should our flights go completely amiss. It would fly solely to reach 8000 feet and return to the ground just to get us on the board. Ultimately, this too would fail.

It was a 54mm, minimum-diameter rocket to fly on a J90W motor using a plastic nosecone found in the rocket room for mid-power rockets. It would carry a Jolly Logic chute release, a PerfectFlite ARPA altimeter, radio tracker, 24" parachute, and paracord shock cord. Because motor-based ejection was necessary, a special plate had to be fitted above the motor with an eye-bolt attachment point and holes to allow ejection charge gases to pass through. This plate was the most difficult part because we sized it incorrectly and 54mm tubes are too small to insert hands. The fins were tricky to keep upright while the epoxy cured and were reinforced with an extra sheet of resin-soaked fiberglass across the airframe and fins. The rail buttons used a well nut that had to be bent to meet the curvature of the tube, so the motor casing could still slide through. Motor retention included a tight friction fit.

Figure 9. Fin aligment measures

Working with a few Speedfest members, Lucas tried to reinforce the flimsy plastic nosecone with a layer of fiberglass. Fitting the cloth alone was tricky, but doable. The Speedfest members insisted on vacuum bagging it as well which was a cool idea until the nosecone collapsed in the low-pressure environment.

The idea for this rocket was proposed on Monday morning, and Wednesday morning at the UAFS, it flew on a G80. To get the 29mm motor to fit, an adapter inside an adapter had to be friction fitted. It flew fine, but the altimeter that had been tied with string was ripped out and fortunately found thanks to its characteristic post-flight beeping. The motor also got ejected out, likely due to the difficulties of friction fitting two motor adapters. It was deemed a success despite reaching less than 1000 feet when it was simulated to reach 1600 feet. Lucas expected it to be related to an improper motor burn or insufficiently located static port holes (not sampling clear, ”good” air).

It flew again in the final 5 minutes of the Argonia Cup after the unsuccessful quad deployment. The first igniter burned but failed to get the motor started. A second igniter worked but the J90 chuffed a bit then took off. The rocket corkscrewed upwards at an angle, not suggesting a high altitude. The simulation put it at less than 9000 feet. The rocket disappeared into the clouds and after a few moments the radio tracker suddenly went silent. Lucas suspected a lawn dart because while an identical amount of black powder was used (0.7g) as in its previous flight, the wide black powder well of the 54mm closure may have meant insufficient ejection. The radio tracker picked up a faint signal, and 45 minutes later it was found buried up to its fins in the dirt. Caleb retrieved a shovel, and we extracted the rocket. A dissection later that night was impressive. Lucas felt that even if the parachute had deployed, it would have been far under 8000 feet. The slow motor start and corkscrew ascent would have all limited its altitude. The Jolly Logic miraculously survived, and the motor hardware extracted. A small portion of the forward section is on a shelf in the rocket room at this time of writing.

H. Building Composites

1. The Fiberglass Tube-Making Process

The tube-making process is a very tedious process with small details becoming big deal breakers. Just to give a small history we started making tubes by casting two fiberglass tubes, one of weave and one of mat, on 2” ID PVC pipe just to get a feel for the process. Here 4 wraps of fiberglass were used and these tubes had to be removed from the mandrel using dry ice to shrink the PVC because only wax paper and cooking spray was on it (this became a bigger problem later on). The next iteration involved making tubes from a 4.5” mandrel, so we would get practice making tubes close to our 5” OD goal. 6 wraps of fiberglass weave were used here, and the second iteration of tubes went on to become Everything is Sticky. This was a significant development for structures, that our tubes were strong enough to withstand flight. After proving our processes were sufficient, the final jump to a 5” OD steel mandrel was made. Here we began producing tubes that would ultimately become our flight vehicle. We made in total 7 tubes on the steel mandrel: 4 being used in flight and 3 being lost due to lubrication issues. The process of making the tubes goes as follows:

1. Preparations
    (a) First cut fiberglass to size
        i. We used 6 wraps of the mandrel and this proved sufficient in strength as well as in weight
    (a) Prep the mandrel
        i. Clean the mandrel with mineral spirits and lubricate with petroleum jelly
        ii. Add a layer of wax paper to the mandrel
            A. Ensure there are no large air bubbles, and the paper must have the non-stick glossy surface pointing outward (if using wax-paper)
            B. Apply a generous layer of petroleum jelly for proper lubrication
        iii. Add another layer of Wax paper to the outside of the mandrel with the non-stick surface facing inwards (towards the petroleum jelly).
            A. The wax paper will stick to the petroleum jelly
            B. The jelly may also be used to tape down the edges of the paper
        iv. Spray this surface with a non-stick spray.
            A. This ensures the paper will easily come off the inside of the tube
    (b) Prepare resin
        i. A tube of 5 OD with 6 wraps will need about 24 fluid oz of resin and a corresponding 240 drops of hardener
        ii. Pour resin in two containers (12 oz containers such as a standard cup) and have the hardener in a separate container (epoxy mixing cups were used here)
        iii. When ready pour the hardener into the resin and mix well
        iv. Wrap the first few layers, then add the hardener to the second container, rather than all the hardener being mixed at once
        v. NOTE: Keep the resin roughly at room temperature. If the resin is to cold it will take a very long time to setup and if the resin is warmed up at all it will set up before the wrapping process is complete.
2. Wrapping fiberglass
    (a) Start by pouring some of the mixed resin onto the top of the prepared mandrel.
    (b) Take the leading edge of the fiberglass under the mandrel and put it on the resin coating
    (c) Gently rub the resin into the fiberglass until it is completely saturated
    (d) Begin rolling the mandrel so that the fiberglass is in slight tension and pouring resin intermittently
    (e) Ensure that all surfaces have adequate resin so that the resulting matrix will be uniform with no noticeable weak points
    (f) Use a sweeping over down hand motion. This will help to properly saturate the fiberglass completely as well as ensure the wrap is tight and free of air bubbles
    (g) Continuing this process until all the desired wraps are completed
    (h) At the trailing edge of the fiberglass be careful to smooth down the edge completely and get rid of any loose edges of fiberglass that might be left, snipping away at soaked strands as necessary
3. Finishing
    (a) Set the fiberglass up to harden. This will take anywhere from 20 minutes to an hour or so depending on the temperature of the room, ventilation conditions, and lighting. (All of this have been observed to affect the hardening time)
    (b) Once sufficiently hardened. Pull tube off mandrel (This will take at least two people typically, one person holding the mandrel one person holding the tube)
    (c) Cut off the edges with a table or miter saw

    (d) Sand to ensure a smooth finish

This process can seem overwhelming but the best way to get good at tube making is to practice. The more tubes that an individual creates the better at it they will become. Some tips though for those who do go on to make the tubes:

1. Use tight fitting nitrile gloves
    (a) The resin is a skin irritant and will slightly burn if it stays on skin for a long period of time
    (b) Use slightly smaller gloves because towards the end, the motion of stroking the resin will gradually pull the glove off your hand
2. Wear clothes and shoes that are safe to get dirty
    (a) This process is very messy (thus the name of some of our rockets) so wear clothes that it is okay to permanently get resin on
3. To get excess resin off your hands use Germ-X or Isopropyl Alcohol
    (a) Alcohol will dissolve the resin making it much easier to remove
4. **BE SURE TO PROPERLY LUBRICATE THE MANDREL**
    (a) This cannot be over-emphasized. If the mandrel is not properly lubricated the tube will become stuck. On smaller tubes such as the original 2 mandrel that was used stuck tubes could be removed with dry ice. However, the bigger the tube the more difficult removing a stuck tube will be, usually results in cutting the tube off the mandrel.
    (b) So, be sure to use plenty of lubricant or mold-release.
5. Give yourself plenty of time. The longer you take on this process the better the product will be. But be sure to move fast enough that the resin that is used will not setup before the tube is finished

Figure 10. The effect fiberglass resin has on our mixing cups, not due to heat

2. *Sheet Making Process*

Sheet making was significantly less complicated than the tube making process described above. Sheets were produced in 12" by 12" sections using pre-existing commercial fiberglass sheet (G10 Garolite) to press layers together while curing. Sheets were made with 12 layers for fins and 8 layers for centering rings and bulkplates.

First, existing fiberglass commercial sheets were covered in wax paper with the shiny side up and sprayed with cooking oil. Next, the appropriate number of layers was cut out of fiberglass cloth with the layers oversized by about an inch in each direction. This insured that the entirety of the 12x12 section was usable. Next, 12 oz of resin was prepared. Then a small amount of resin was spread onto the bottom wax paper covered plate before the first layer was set on.

Resin was added between each layer and smoothed with a flat plastic scraper. After the last layer the top wax paper covered plate was placed on the layup and weights added to ensure an evenly packed layup. Its best to brace the weights against the table in some way to prevent the layers from sliding before they cure if the table is even a little bit tilted.

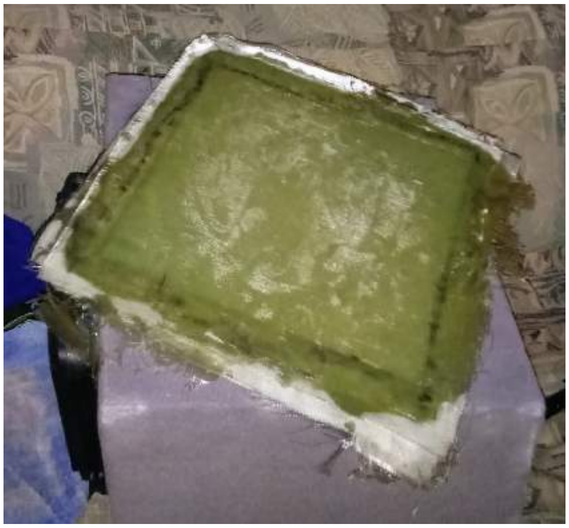


Figure 11. A 12x12 sheet with edges uncut

Figure 12. Edges being trimmed from the sheet

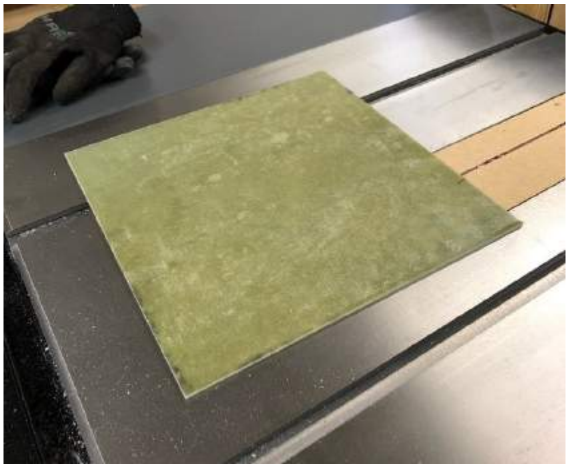


Figure 13. Finished sheet, ready to be CNC cut

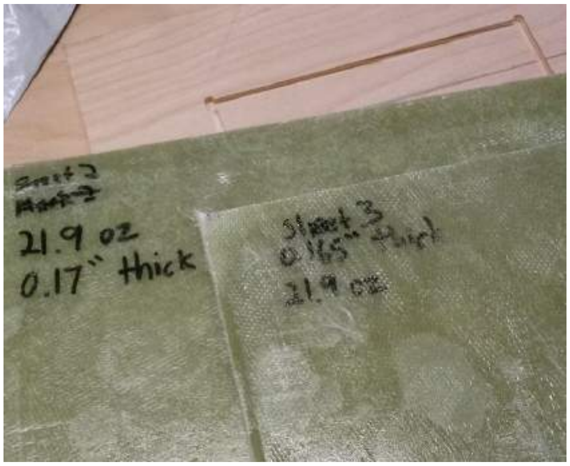


Figure 14. Specs on first few sheets

3. *Coupler Making Process*

The coupler making process is much like the tube making process with some slight modifications due to the smaller size. For couplers there are really two options: making your own, or using commercial couplers.

Buying commercial is much more expensive and will require some more work later to ensure that fit is proper since the tubes being made are not perfect. Also, if commercial couplers are used, then long sections of commercial couplers can be used as the casting mandrel for the tube making process. Here the process of making your own couplers will be discussed. Making your own has several advantages one being that it is much quicker to get a product (you do not have to wait for shipping/delivery) and it is much more cost effective than buying commercial couplers.

1. Preparations
    (a) Finish making the tubes that the coupler will go into
        i. This will help determine what size the 3D printed mandrel needs to be since the tubes will have slightly different ID
        ii. Take the average of the ID, subtract thickness of the desired coupler and that should be OD for the mandrel
        iii. 6 wraps of fiberglass corresponded to an average of 0.07 of tube thickness for us
        iv. 3D print this mandrel to slightly more than the desired length
    (b) Once the mandrel is printed take a tight layer of wax paper to the mandrel
        i. Ensure that the ”wax” non-stick side is outward
    (c) GENEROUSLY APPLY petroleum jelly. This is important because if the tube get stuck the it will be hard to remove the mandrel without breaking it
    (d) Apply another layer of wax paper with the non-stick side facing inward
    (e) Apply a non-stick spray coating to the other side
    (f) Prepare resin exactly like before
2. Wrapping
    (a) The wrapping process will be exactly like tubes
    (b) Be sure to keep a good amount of pressure/tension in the line so that the outside diameter will be as uniform as possible
3. Finishing
    (a) Set to harden once the wrapping is done.
        i. If all is done correctly the couple should be removed with little to no difficulty
    (b) Cut edges to clean it up
    (c) Sand the exterior to and ensure that the fit between coupler and tube is proper (Coupler should slide inside somewhat easily but not simply drop through the tube)

This process is remarkably like tube however, there are some important differences and things to note.

1. 3D printing is tough but not super strong
    (a) It will break if the tube gets stuck or any of the wax paper leaks resin
2. Be aware of the lead time of printing and how you are going to attach different print
    (a) If the mandrel is made of two different sections be sure you have a good way to connect them.
        i. One good way we found was to glue dowel rods to the inside. Just make sure that the two parts are flat and butt together nicely.

Figure 15. Piston, *The Other Things* altimeter bay, and 3D-printed mandrel glued together

I. Final Comments

1. *General Comments on Making Fiberglass Parts*

1. Be prepared for thicknesses and weights to vary, even on the same piece.
2. Always oversize parts (primarily centering rings) so that sanding can get the appropriate fit. For example, a centering ring should be sized by a few extra hundredths of an inch smaller than the OD of the motor mount tube, and larger than the ID of the airframe tube. If parts are slightly loose, it is alright as long as sufficient epoxy fills all of those gaps and the part is in the correct position and orientation until the epoxy is still enough to hold its weight. The orientation is especially important for centering rings that they do not become lopsided.

2. *Other Comments*

1. When threading holes for shear pins, don't thread the inner tube part of the hole. If the shear pin doesn't come out properly or gets cross threaded, it is easy enough to remove the external shear pin, but the inner one is far more difficult. Usually a drill is the only way to actually remove the inner one if it is stuck and drilling that hole again will damage the hole itself.
2. When tying the parachute knot on the shock cord, never tie that loop further than 2 down from the separation point. For example, if the nosecone is being ejected, tie the parachute loop on the shock cord 2' from where the shock cord is tied to the nosecone. This ensures that as long as the ejected parts are flung a few feet apart, you increase your chances of the parachute being exposed to air. It'll do the rest of the work from there.
3. This may pertain more to cold weather when parts are less flexible, but we observed that when we folded our main parachute, in particular, it became stiff when it sat for hours folded inside the tubes. This could potentially make it harder for the parachute to unfurl. If possible, fold and insert recovery components close to launch time.
4. 3 plastic rivets are sufficient for L flights. Aluminum tube fasteners from Apogee are nice, but expensive and overkill for these projects. Plastic rivets worked fine for us.
5. 3D-printing should be kept to a minimum on rocket hardware. Ejection charge caps and rail buttons are excellent when 3D-printed. Some altimeter bay parts may also be printed, but we prefer to make the sled out of wood and then epoxy on the necessary parts for threaded rods and other parts. 3D printing is time consuming, not always available, can fail mid-print, and some plastics can warp in the heat of a car or when sitting on a launchpad in the sun for an extended period of time.
6. The following rocket materials were purchased by Dr. Jacob in 2018 for this capstone project that are left over in the rocket room: the RRC3 Sport Altimeter, 98/5120 motor casing, 98mm forward

closure and eyebolt, 98mm aft closure and eyebolt, 98mm forward seal disk stainless steel (used in Super Thunder propellant reloads, purchased for DOE Rocket), Aerotech K780R motor reload, 5" vacuum-rated steel pipe, heavy-duty scissors, the shear pin hole tap, the Madcow Mad Dog "DOE" Rocket kit, the 10' 1515 aluminum launch rail, SkyAngle Cert-3 XL parachute (big yellow and orange parachute), the 80' of blue 1" nylon shock cord, two 98mm Aeropack motor retainers, 98/75mm motor adapter, and all the Wildman motor igniters (the white and colored twisted wire igniters). There of course were other parts, but the above listed ones are ones that the rocketry team can use, but next year's capstone team should then take priority for 2019. In 2018, each registered team received an Altus Metrum EasyMini altimeter for registering. The rocketry team also got one. One of these belongs to next year's capstone team as a result.

7. The following were consumables from the rocketry team: I357T, J90W, I500T, model rocket wadding, and black powder.

3. Improvements for Next Year

1. An on-campus place to make tubes and sheets is needed. We used Chad's garage because no one gave us a place at the DML or elsewhere to make our parts. This worked well because we could work any time of day or night without ridiculous safety measures, DML staff, SOPs, or Speedfest people to get in the way. We did however get resin everywhere and ruined a wood table in the process. It was also not well ventilated, and we sometimes got coordinated headaches. We think your best bet is to use the Aero Assembly facilities in the DML that the Speedfest folks and Dr. Arena's grad students use. We're sure they will have their own rules and critique the methods, so be aware of that. Dr. Arena doesnt have any expertise in rockets, but they know a lot about composites. He and Collin are pretty cool about our rocket work, too. More so than John Gage or Dr. Conner at least.

2. Need an on-campus place to cut tubes to length (miter saw, or table saw). Lucas' roommate, Alex had an extensive personal wood shop, and his table saw was used to cut the ends off tubes, cut tubes to length, and cut the sides off of sheets. John Gage allowed the rocketry team to use a miter saw in the past for fiberglass in the high bay. Again, an advantage of using personal equipment was the ability to do this work anytime.

3. Need on-campus place to CNC cut sheets for fins and centering rings. Alex bought his own CNC just weeks before the semester started. It was an Inventables CNC that Lucas learned to operate. The rocketry team paid for a new routing bit as replacement at the end of the project.

4. Just before the Argonia Cup, Lucas was working on some electronics in the rocket room, and Dr. Conner came in saying he smelled "polyester resin." Lucas truthfully didn't know of any such resins. We had spray painted to the night before and brought the painted parts in to dry, and Lucas had just mixed epoxy, but he wasn't away of polyester resin. Dr. Conner said polyester resins cannot be used. After some research, the Bondo Fiberglass Resin is a type of polyester resin, and Dr. Conner had smelled the tubes. It may be necessary to use epoxy resin over fiberglass resin in the future. Fiberglass resin isn't as strong and doesn't smell as bad but costs many times more than fiberglass resin. This may be alight from a cost standpoint because little or no experimentation may be needed now that the process is better understood for tubes and sheets.

5. If you can use fiberglass resin with the same methods used in 2018, there will be little to no need to verify the abilities of fiberglass parts as long as someone is familiar with the process (Structures team members of the rocketry team), so this should make a meaningful launch possible in February (we had to use that February launch to validate our composites as we were still learning and scaling up).

6. Parts that should be purchased for separate use from the rocketry team's materials: soldering iron, 18-22 AWG wire, precision screwdrivers,

IV. Integration

A. Goal

The Integration Team was charged with designing/modifying a recovery system capable of carrying a golf ball payload back to the launch field, fitting this system into a rocket body tube which is essentially a hollow cylinder of a later determined diameter, and ensuring that it did not interfere with the rockets minimum required altitude of 8000' AGL, upon a limited motor size.

B. Initial Constraints

Our designs were primarily constrained by the size and weight of the recovery system as the most significant qualities which affect the flight characteristics of the rocket. Other constraints to our design process were the total cost of the system as a whole, the ease of manufacture for all system components, and fool-proof deployment from the chaotic environment of a rocket during flight. With these in mind, the team as a whole came together to establish the primary goal of winning the competition and choose a system based on the above constraints that the team was confident in its ability to possibly fulfill our primary goal.

C. Overview and Design Direction

The beginning of the design process began with brainstorming ideas of systems that would give the best opportunity to fulfill our teams stated primary goal of winning the Argonia Cup. The major ideas put forth were a low altitude parachute, a full rocket quadcopter, an integrated/deployed quadcopter, a full rocket glider, and a integrated/deployed glider. Initially, the team was in favor of a full rocket quadcopter, but after realizing the constraints of the weight due to the motor size, this was deemed impractical. Also with the chosen goal of winning the Argonia Cup, that design did not make sense as there was no need for the whole rocket to return, just the payload. After completing the analysis of the pros and cons, as well as a full design matrix, the team settled on an integrated/deployed quadcopter as the chosen path. In initial designs, the integrated/deployed quadcopter was either going to be ejected via a sled system as it was in the 2017 Oklahoma State University High-Powered Rocketry Club's (OSU HPR Club) design or be fit into the nose cone of the rocket and ejected at some point during the flight. Because of the size constraints of the inside of the tube, the nose cone quadcopter was chosen. The figure below shows the initial design of the quadcopter.

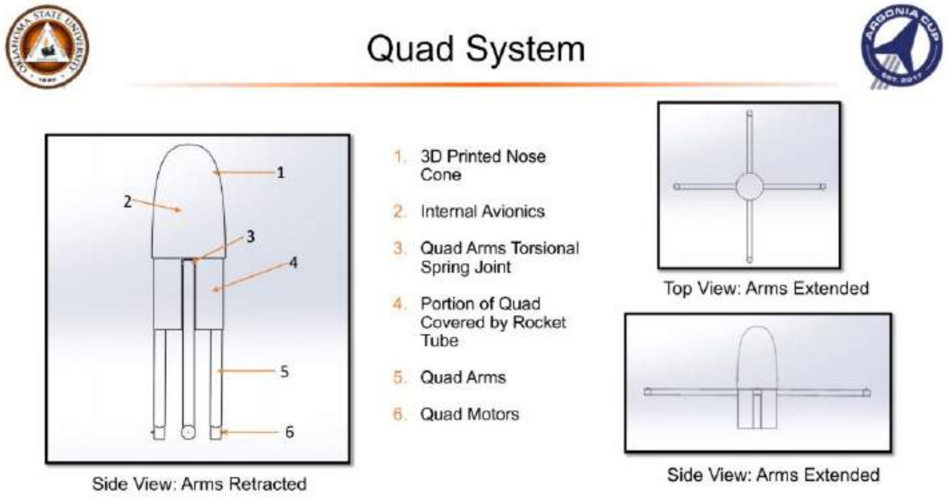


Figure 16. Quad System

As the Integration Team, our responsibilities were to create the physical structure of the quadcopter and the different parts and mechanisms that it needed to operate. The quadcopter needed its arms to be able to fold and extend in order for it to slide into the tube. At some point after launch, it would be ejected and the arms would need to fold out to allow the motors to start while the propellers spin unhindered. Folding propellers were a necessity, even at this point in the design, as whatever ejected the quad needed to have a solid component to push the quadcopter by. It also kept the issue of the propeller hitting the side of the tube just after ejection. After an initial verification that a 3D printed nose cone could survive the forces of launch, we moved forward with the concept of having a majority of the structure being 3D printed to better cater to our design requirements, create more complex structures, and drastically speed up the prototyping phase.

D. Quadcopter Body Design

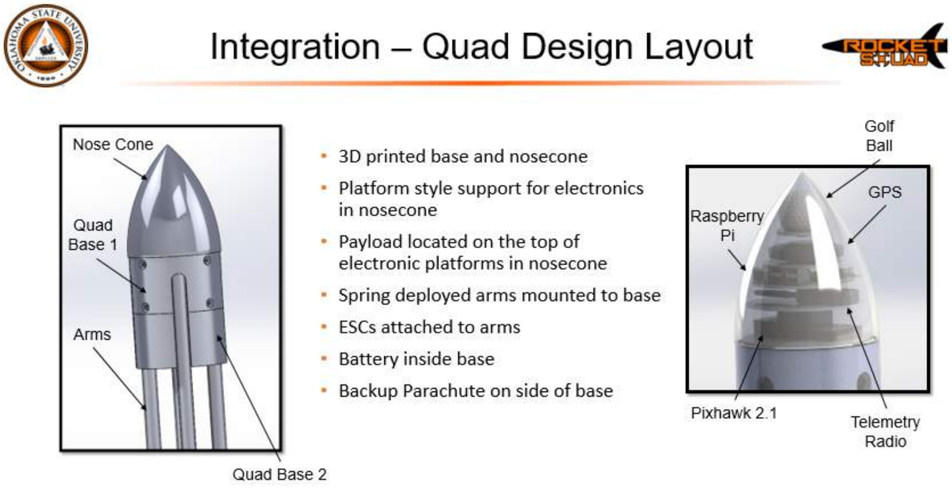
With the resources of campus and previous experience of our team captain, Nicholas Foster, it was quickly decided that the quadcopter body structure would be done via 3D printing using PLA (polylactic acid) for the prototyping and then printed on an SLA (stereolithography apparatus) printer or nylon if possible. This was because PLA is relatively weak compared to SLA or nylon, but cheap and quick to test out iteration after iteration of the structure. 3D printed plastics also reduced the cost and weight as well as giving many more possibilities compared to commercial components. The resources available for the team also allowed for multiple portions to be printed at the same time in PLA, which is very valuable for rapid prototyping and with the extensive print times that would end up being needed, getting a full quad printed in a matter of a day or two.

The structure needed to be able to have the 2" x 2" area of the battery fit inside of it as well as the wires which handled power distribution. This constraint was decided on early in the design as the side of the quad and the flight time needed would require a battery of this size. We also had to utilize our space as efficiently as possible with the electronic components, particularly because of specific placement requirements of the flight computer. Initial mockups were created to verify that the design layout would have enough room to accommodate all of the contents. All of the avionics was designed to fit in the nose cone and the battery would fit inside of the bottom portion of the 3D printed structure, along with other miscellaneous electronics.

After this step, it was noticed that very little access to the bottom portion would be available after the battery was inserted. This led to the complete structure being split into three separate portions; the bottom base for the battery and various electronics (First Person View camera, emergency backup parachute, wires, etc.), the mid section for for the arms to connect to with the springs and the electronics structure also fastened to it, and the nose cone itself that will act more as a cover for all of the electronics and its structure. The three sections are featured below in the left side of the image on the "Integration - Quad Design Layout". Everything was designed to be riveted together via nylon rivets in a similar way that rocket sections are fastened together. The body design as a whole stayed consistent throughout the design process, with changes occurring to some of the internal layout to increase the strength of specific portions as well as some sizing adjustments to allow the sections to fit together better, whether that be more loose or more snug.

E. Electronics Structure

The initial electronics structure came to be because of where the pixhawk had to be mounted, just above the center point of the arms in order to properly control the quadcopter, as well as the size of the electronics being mounted there. It was known pretty early on into the conception of the quadcopter that the electronics were going to be kept in the nose cone for easy access. This created a new set of challenges particularly with the conic space limiting what could be placed within the piece passed the initial opening. After some initial thought, this almost created a natural hierarchy with the Raspberry Pi stored below solely because of its space requirement, then the pixhawk and telemetry radio merged onto a single plate just above the arms for control, then the GPS unit above for a clear connection and finally the golf ball at the top because it fit perfectly and would interfere with the placement of other components if it were to be placed in the body of the quadcopter. Two threaded rods and plastic standoffs forming a rectangular pattern were also added between each layer to connect everything together. The threaded rods were screwed into holes printed into the material and added support as well as rigidity to the structure, while each plate rested naturally upon the the standoffs printed into the plate itself, isolating each level and creating another layer of protection for the quadcopter control systems. The manufacture of the threaded rods primarily was cutting " threaded rods to 4" long. Each side was cut using a grinding wheel as fine precision was not necessary. The cut ends were then filed down until the threads were all able to be easily screwed into a nut of the correct size. A version of this is featured immediately to the left of this statement.



Integration – Quad Design Layout

- 3D printed base and nosecone
- Platform style support for electronics in nosecone
- Payload located on the top of electronic platforms in nosecone
- Spring deployed arms mounted to base
- ESCs attached to arms
- Battery inside base
- Backup Parachute on side of base

Figure 17. Quad Design Layout

F. Realized System Design

As previously decided, the recovery system was made up of a quadcopter with four downward folding arms. The 3D printed quadcopter body had cavities in which the arms would fold. Once fully folded, no portion of the arm should protrude further than the body itself so as to not create interference with the rocket body. In order for the arms to properly fold completely in place, it must be cut to an appropriate length which also allows the propellers and ESCs to not interfere. The propeller radius was previously determined to be 7.5”, and this propeller distance had to fit between the motor and the lowest point of the quadcopter body. An arm length of 12.5’ allows enough room for the propeller to fold into the quadcopter body without being obstructed by the quadcopter body itself. In the photo below, there is an example of a folded arm adjacent to an unfolded arm. With this illustration, you can see that the folded arm is in line with the wall of the quadcopter body and there is enough room for the propeller below the quadcopter body.

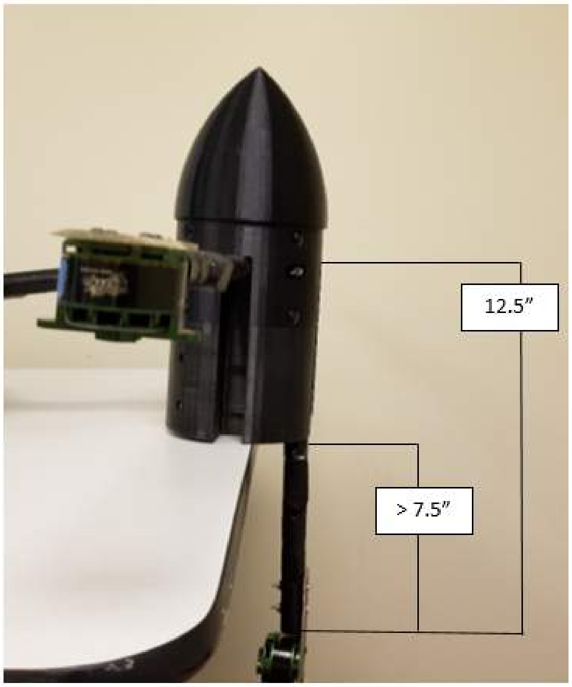


Figure 18. Quad Side Dimensions

Now that the arm is cut to the proper length which allows for the propellers, the design must now consider the placement of the ESCs. Each arm must have an ESC firmly secured between the quadcopter body and the motors, yet they should close to the motor. The arms are roughly 3/4" in diameter which does not allow for enough space inside for the ESCs. Due to weight and space considerations, it would be a poor decision to scale up the arms just to fit the ESCs inside, and it is for this reason that they must be mounted on the outside of the arms. When the arms fold down, there is very little space between the arm and the quadcopter body, so the ESCs were placed on the 7.5" portion of the arm nearest to the motor which would be below the body in the folded configuration. As for ESC orientation, it was determined to be best for space considerations to face the ESCs towards the inside of the tube. In other words, the ESCs would be on the opposite side of the arms from the side of the arms which would make contact with the rocket body. Two holes were then drilled through that same side of the arm which would be used to allow the ESC wired to be run through the arm, out to the ESCs, and then back into the arm until reaching the motors. Much of this was practiced on various inexpensive PVC pieces which caught many mistakes early and limited issues in future steps.

Once the team was confident that the arm would fold properly which each component attached and not interfering, the motor mounts were designed. Due to our early success with 3D printed components, the motor mounts were drawn up in CAD. By printing the motor mounts, we hoped to keep them light and uniformed dimensions. It is important that each motor is equidistant from the center of the quadcopter, and for this reason, the arms and motor mounts had to be kept the same length. The motor mount would tightly rap around the end of the quadcopter arm, and there is a space through which the motor wires could be fed from the ESCs to the motors. Additionally, each motor had four screws to be used to secure the motor to another surface. The motor mounts were designed with four holes through which the motor would be mounted. The CAD rendering of the motor mounts can be seen below:

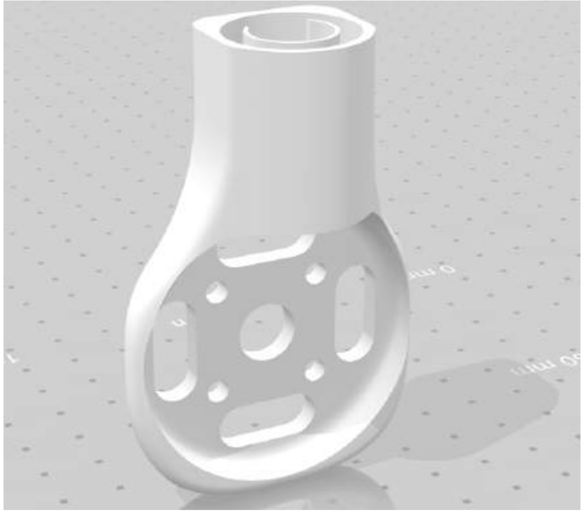


Figure 19. 3D printed motor mount CAD

G. Mechanism and Component Design

1. *Arms and Springs*

The first major component design that we focused on was the the mechanism that was to extend the arms. As a team we decided to avoid any powered mechanism such as a motor or a servo, as this would use up battery life, which we knew was going to be a constraint on our system. Not only this, but space and weight were the highest constraints on the quadcopter at the time and motors are extremely heavy and bulky. Another issue was the weight of the motors on the end of the arms, which added a significant amount of force, amplified by its distance creating a substantial moment, for our mechanism to have to withstand and work against to complete its actuation. It also came to be that if the quadcopter sat flat, that the force that needed to be overcome increased as the arm extended. Considering all of this, torsional or linear springs were the only option that made sense. While they both have their perks, linear springs would have required a lot more space within the quad and the springs with the required criteria were rather heavy. Torsional springs gave us exactly what we needed in compact placement and a significantly appealing strength to weight ratio. McMaster-Carr carries an extensive supply, and after testing by making a model out of a PVC (polymer of vinyl chloride) arm with a weight on the end, the perfect springs for the job were selected. Initially, we sized our first batch of springs from our calculations of the amount of torque required to lift the known mass of the motor assembly the required 90°.

However, this quickly proved to be a gross underestimation of the abilities of the springs, and over successive iterations, we learned a couple things specifically about torsional springs. First, the maximum torque from the spring is subject to a lot of variance as it is given at its maximum deflection, especially when placement may not be ideal, so a little oversizing is ideal. Second, a spring that has the exact flexure for the range of motion that is required (90° spring for 90° range of motion) will not work, the torque of a spring is not its full amount for at least the first 30% of its range of motion if not more, meaning at least in our case, that the quadcopter arms when released would be flung to their full open position, but could not be held there and found their resting position at approximately the 45° mark.

To counteract this, we began to look into possible locking mechanisms, but few of the brainstormed ideas stalled as space and weight constraints became too restrictive as well as the possibility of vibrations during flight interfering with the function of the mechanism. The decision was made to forgo a locking mechanism unless it was determined to be necessary with more complete assemblies and deployment testing as it was just additional weight. Those concerns were also alleviated with the knowledge that the thrust produced by the motors would always push the arm in the extended direction, holding them extended if necessary, but a mechanism could always be designed if absolutely needed.

We then chose to utilize springs with a 180° range of motion to ensure it would apply a constant amount of force to hold up the arms when they reached their max deployment at the 90° mark. The springs we chose are shown below, each arm uses a left hand wound as well as a right hand wound spring to ensure an even force distribution as well as confidently hold the weight of the arm and motor assembly. Modifications to the springs were made by bending the leg of the spring that touches the arm. It was bent in to slide into a hole cut into the arm. The correct amount of bending in the direction of the arm was necessary as to ensure that it could fit in the gap in the tube but also not interfere with the spring leg on the other side of the arm. The other leg of the spring was bent around in a circle to provide a solid platform for the reactionary forces to be applied to the structure of the quadcopter with the goal of reducing the possibility of them breaking through the plastic or causing any wear damage. This also kept them out of the way and had the byproduct of being aesthetically pleasing in the completed quadcopter by hiding them from view. The bending was performed by using a vice to tighten a portion of the leg and needle nose/regular pliers to bend at specific locations and angles. The process was trial and error until the necessary shape was created. Some springs may fit better in specific arms because of the errors in manufacturing, so it is good to test each spring on the arm that it will be used in and keep them together. One needed to be careful as too much bending back and forth at one location can cause the spring to break at that point as well.

Figure 20. Arm springs

Figure 21. Arm spring system

The next issue was what material to use for the arms. High strength was needed, so carbon fiber tubes were selected. To avoid stress concentrations and because of the availability of sizes and shapes, 20mm x 18mm (Outer Diameter x Inner Diameter) tubes were chosen. The tubes are the perfect size and are relatively cheap online. Carbon fiber needs to be drilled wet, so WD-40 was decided as the liquid to drill it under when machining occured. When drilling, very high speeds were needed and steps in drill bit sizes are required. Our team used ” steps in sizes on a drill press. For speed requirements, look to a material machining requirements list. For testing purchases, ” PVC (.84” actual Outer Diameter) was chosen because of its ease of purchase, easy machinability, and relative strength. The decision to use 3D printed motor mounts on the end to attach the motor to and slide onto the arms, as shown below. The Electronic Speed Controllers, or ESCs, would run wires inside and rest on the outside of the arms. This would protect the wires as well as allow the ESC to stay cool through airflow.

The pin that the arm would rotate around was the next issue. Testing was completed with a ” bolt that ran through a hole in the 3D printed base, through a spring, through the tube, through the other spring, and back through the 3D print. A nut would then hold the bolt in. After initial testing this size was not sufficient and was bent, so ” bolts were then used. They were purchased from Lowe’s and were 2.5” long ” bolts.

H. 3D Printing and Manufacturing

The initial design of the 3D printed structure can be found in the first revisions of the the SOLIDWORKS files that are included in the design package. A few images are shown below of the initial and close to final designs.

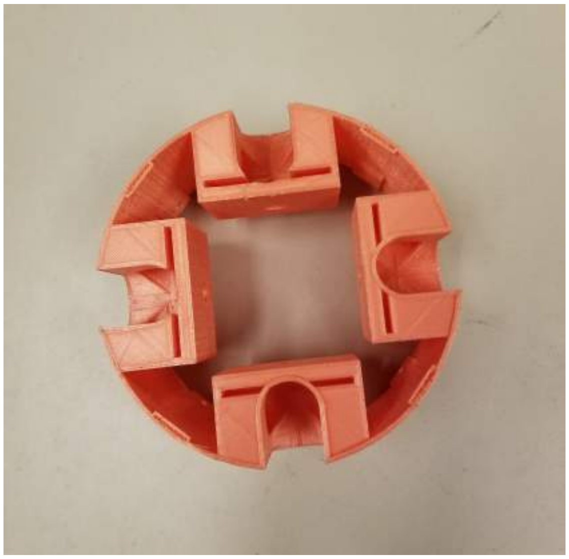


Figure 22. Initial Body Print

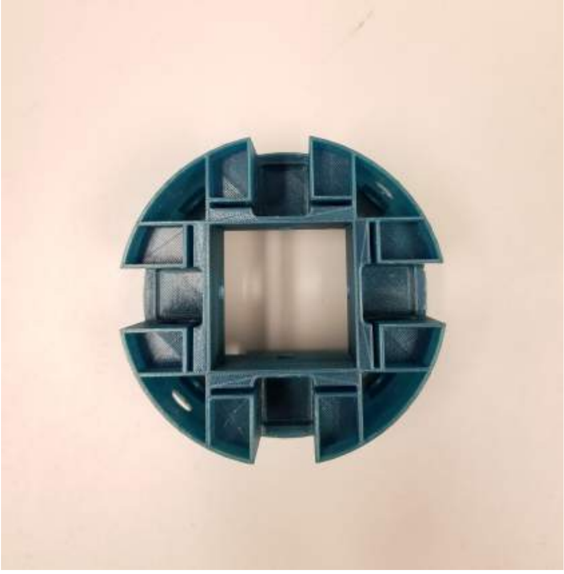


Figure 23. Iteration of Body Print

We choose to print these structured with a higher than average wall layer count as well as a maximized infill between 80% and 100% depending on the piece that was being printed. While seeming excessive, a lot of the forces were being concentrated on a few thin areas of the plastic and these choices were made to increase the durability of the printed quadcopter as a whole. One major lesson learned is that the print strength and print times quickly became a limiting factor for us. The quadcopter bottom section, mid section, and the nose cone took approximately 24 hours or more to print each. This caused the Integration Team problems on numerous occasions when a test didn't exactly work out and we had to start the printing process again in order to continue testing. This possibly could have been balanced by having backups already printing or printed and ready to go, however this would eliminate the freedom to adjust the design if a change was determined to be needed.

In addition to this, despite our initial desire, there are some pieces that could not and should not be 3D printed, specifically this refers to the motor mount pieces at the end of the quadcopter arms. These pieces, were simply unable to cope with the stresses induced during a flight, namely the pieces would break under the motors own thrust as shown in the figure below. Every single printed motor mount test broke in the same location. After numerous iterations of these pieces, it was eventually decided that the size constraints and location of the holes created too high stress concentrations and the material was changed to fiberglass, where this new design is discussed further below.

Figure 24. Printed motor mounts

I. Major Issues and Design Changes

Some revisions were made to stiffen the midsection up. Separation between layers and cracking because of the impact of the arm on the print made it necessary to increase the fill rate and add some more wall thickness. The critical points near the corners of where the arm cut-out is the cause of a majority of the cracking. The largest revisions included connecting all of the arm/spring housings and increasing the fill up to 100% for PLA. SLA is always 100% infill so the conversion that print type had no issues.

Fillets were also added in the corners of the arm section to keep the material layers from separating as it had become an issue. These changes allowed the arms to extend without any damage to the 3D printed structure. It took some fine tuning between iterations to get the arm to stop at exactly 90° when extended. There are two holes on opposite sides of the mid section that allow the arm pins to be inserted after the springs and arms are in place. Each hole would have both of the screws on that half inserted through there, and these holes would also help designate the left from the right side of the quadcopter later on.

Sanding needed to be done to allow all of the pieces to connect to each other. Minor changes to the dimensions was made to allow their assembly with slightly less sanding and friction. This is especially important because extensive sanding weakened the print's wall layers and created points of possible failure. Also when the SLA print was completed, very extensive sanding had to be done as the dimensions were slightly bigger than the design dimension. This was an unforeseen issues as SLA is supposed to print to nearly the exact dimension, which is technically correct as further research showed that SLA prints typically end up approximately 2% larger than its CAD specifications. It was tougher, but slightly more flexible than PLA. Nylon was researched, but the expense of printing the pieces would be just too high for the project budget, nearly $600 for all three sections.

After the almost full scale deployment test, featuring the entirely SLA printed quadcopter, minus motors and electrical components, which crashed, it was noticed that SLA was brittle and fractured into countless pieces upon impact. As an aside, the SLA broke like a injection molded hard plastic would be expected to, there were no separations between layers and it had no definable patterns. As a backup, we knew that the partially filled PLA was strong enough to work and led to the decision to use PLA for the competition quadcopter. SLA had to be 100% fill so being able to print PLA at a lesser percentage of infill, and reduced one of our concerns with the weight of the system

The nose cone was slightly altered from the first iteration to make it less blunt and reduce its thickness as well. Other than this, a few other dimensional changes were made to allow it to rest on top of the electronics structure bottom base and hold it down. The quadcopter bottom base has a cutout for a First Person View camera and a chamfer was added on this edge to make the field of view more open. The parachute system was changed to a black powder charge, after initial designs of a spring powered system, and initiator set off by a transistor upon receiving a signal from the Raspberry Pi. The spring system was just too large to fit in the space available. The fairings, printed material that the parachute was encased in, were changed to be able to slide out easier. There was still enough friction when the parachute was inside it not fall out at launch. The folding of the parachute was a traditional rocket parachute folding method and the paracord that connected the parachute to the quadcopter bottom section was housed on top of the fairings.

The springs ended up getting a portion of the legs cut off on the side that was in the 3D print. This was done using a cutting wheel of the Dremel and slicing off around ". As the material is music wire, a simple wire cutter will not cut it efficiently. This was tried initially and it damaged the blade of the cutter. Once it was removed, no issues with the leg interfering with the body of the spring or in the assembly of the two bottom sections occured. A top and side view of a finished spring is shown below.

Figure 25. Spring side view

Figure 26. Spring top view

J. Motor Mounts

The printed motor mounts turned out not to be able to handle the forces of flight and as stated above, the thrust of the motor repeatedly broke the mounts. To fix this issue, fiberglass sheets created by the Structures Team used for the rocket fins were cut into a semblance of the motor mounts shape. They needed to be wide enough as for the holes not to create a large enough stress concentration to break. Holes were drilled for the bearing and screws of the motor and for screws to attach to the motor arm. The first iteration was too thick, 0.18", and scraped on the tube when inserted. The second ones were slightly larger " (0.13") thick and fit perfect inside the tube. The figures below shows the final version.

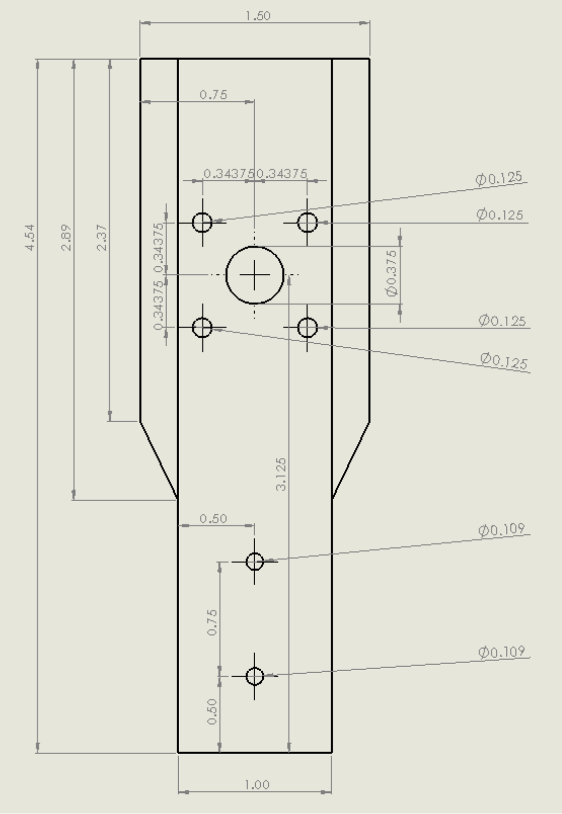


Figure 27. Motor mount top drawing

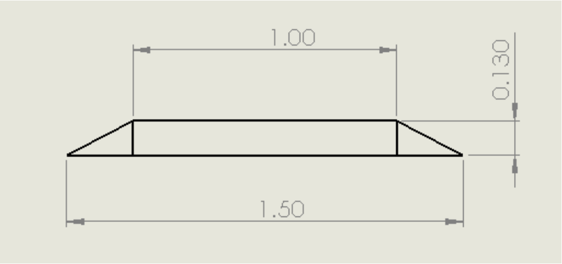


Figure 28. Motor mount front drawing

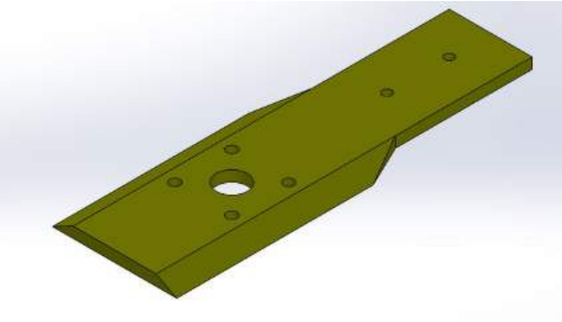


Figure 29. Final motor CAD model

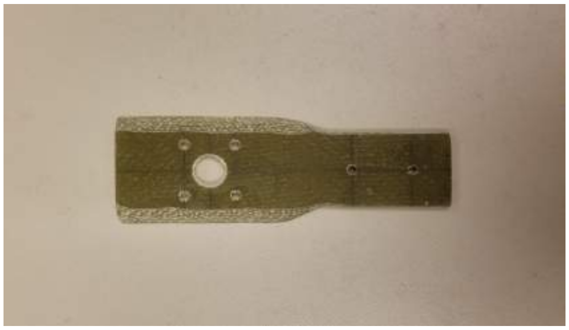


Figure 30. Final motor design

The orientation of the screws on the motor mount had to change slightly so all of the heads were on the outside (same side as the chamfer on the motor mount) when folded up. This was derived from the issue of the screws scraping on the tube as it slid in and out because they were too long. Another alteration was added by creating the chamfer of the wider side of the motor mount. This was completed by using a sanding wheel on a Dremel and creating an angle that led from the bottom to the 1” wide portion as shown in the figure above. It was an extremely tight fit inside tube originally, but after the modifications to the motor mount by using the thinner thickness, added chamfer, and picking the right screw orientation to not stick out far, the issue was fixed. The screws were still the things that scraped, but this was deemed unavoidable and did not create very much friction. Very little effort was needed to slide it in and out of the tube.

K. Arms

All initial testing on the quadcopter was accomplished with PVC arms, and this included drilling holes, motor mounting, arm deployment, quadcopter deployment, and even flight testing. The goal was always to use carbon fiber arms in the final design, because carbon fiber arms would be thinner leaving more room inside for wires, they are lighter, and they look much cooler than PVC. The driving consideration in most design choices was weight, and each carbon fiber arm would be roughly 20g lighter than a PVC arm which is a significant difference. However, there were known issues with using carbon fiber. First, you can't find 20mm diameter carbon fiber tubes at Lowe's, so they had to be ordered online which took a while to ship. Second, they only came in 500mm sections meaning we had to buy several without using all the material, and it cost \$50 for one set of arms which is significantly more expensive than PVC arms. Lastly, the quadcopter arms required several holes, and due to the high strength of carbon fiber, strength wasn't the primary concern. Carbon fiber is tough to cut and drill, because for the best results, the material should be lubricated while being cut or drilled. This required the team to take much longer to manufacture the arms, and the pressure was high to get it right due to the cost of material and time to ship.

After successfully manufacturing a full set of carbon fiber arms, the team was very pleased with the appearance of the arms after a visual inspection. However, immediately when the team began lacing screws on the arms and securing the arms to the quadcopter body, we began to notice very small cracks. When the arms are test folded, there was a noticeable crack which worsened fears that the arm strength was compromised. The team next test flew the quadcopter with the carbon fiber arms, and it was during the test that one of the arms took a blunt impact which sheared out the hole which held the arm bolt. The cracking is obvious in the photo below.

Figure 31. Cracking carbon fiber arm

Despite all the work put into preparing carbon fiber arms, it was clear that it had no chance of surviving the stresses required of the quadcopter arms. Considering the success with the PVC arms during all previous tests including rigorous flight testing, the PVC arms were the obvious choice from a reliability standpoint. The arms were replaced with the PVC arms, and there were no more concerns with arm strength. Although not ideal, there was enough of a buffer in the weight budget to allow for the heavier PVC arms. From this lesson, the team learned to go with what works despite the fact that we were so focused on using a material that clearly wasn't going to cooperate.

Although the ESCs were purposefully placed in order to prevent them from interfering with the rocket wall as the quadcopter ejects, the ESCs experienced a different issue with its placement. By placing the ESCs on the inside of the arm in a folded configuration, it was in the same plane as the propeller. During steady and level flight, the propellers spun without interference; however, the propellers did have some flexibility. During a preliminary flight test, the quadcopter experienced dynamic flight conditions which led to one of the propellers flexing and hitting the ESC immediately above it. This anomaly caused the quadcopter to fall out of the sky, and although there was little damage, the issue needed to be corrected.

The ESCs could not be on the upper side of the arm to prevent interference with the rocket body in the folded configuration, and now the team knows that the propellers may hit the ESCs in the previous configuration. This leaves the sides of the arms perpendicular to the plane in which the propellers spin. The quadcopter has two motors opposite from each other that rotate clockwise, and the other two rotate counterclockwise. The ESCs were placed on the side of the arm that is opposite from which the propeller spins towards. This requires two arms with ESC holes on one side and the opposite on the other two, but in this configuration, the ESC is protected by the arm as the propeller would hit the arm rather than the ESC in the worst case flying condition. Additionally, by removing the ESC from between the propeller and the arm, there is more clearance for the propeller to flex, and less likelihood of an impact as a result.

It was during flight testing where we found most potential flaws in the quadcopter design, and one issue was in the motor mount screws which secured the fiberglass motor mounts to the quadcopter arms. During one flight test, the quadcopter bean to wobble and lost the ability to maintain a level flight. After a less than ideal landing, the motor mounts were noticeably loose. During the flight, the bolts which held the fiberglass motor mount securely mounted to the arms shook loose. The bolts were again tightened and duct tape was wrapped around the motor mounts to prevent the loosening previously observed. The quadcopter then flew without the issue recurring which verified the team's theory. This problem was permanently fixed by putting Loctite on the motor mount screws, and the motors did not shake loose afterwards.

L. Other Manufacturing Considerations

Time was our biggest issue for this project. With parts that would take more than 24 hours to print as well as orders for quadcopter parts and electronics taking 3 days at a minimum, we would have much rather started the prototyping significantly earlier and fleshing out the final aspects of the design even before the PDR. That being said, there is always the possibility that an order just gets held up, we ended up having one order that was placed at the beginning of Spring Break and didn't arrive until the end of April.

For the Carbon fiber arms, there were some precautions that we needed to take in order to keep the pieces structural integrity. Primarily when cutting or drilling the carbon fiber, it is paramount that a lubricating fluid is used to remove excess heat from the piece. The fibers of carbon fiber are bonded together using an epoxy resin, which will melt/vaporize as the material heats up, either delaminating the layers as a whole or leaving frayed carbon fiber fibers that will, over time, reduce the adhesion/continuity of the composite causing early failure. Special considerations should also be made when choosing to use carbon fiber since it is conductive. The carbon fiber is able to absorb radio signals because of its natural conductivity. It is important to treat these pieces as if they are metal to ensure proper precautions are taken.

Utilizing the schools 3D printing resources imparted no cost to us for any of our prints, yet because of the large print times it was deemed necessary to utilize outside printers. While this ended up costing for each print, the cost of PLA filament spools was an extremely affordable expense considering that we could print approximately three, 300 gram pieces from a single kilogram spool.

M. Final Design and Performance

The final design for the quadcopter was finished just before the Argonia Cup. Minor issues and adjustments were being made up to the day of, and in between, launch days to allow for the best possible chance of success. The final revision of the arms are 12.5" long PVC arms, as the carbon fiber cracked extensively, with all of the necessary modifications to allow for the ESC wires to fit and inside of the tube and for the motors to be easily connected. It is recommended that the ESCs being inserted and taped, the motor mounts be attached, and the motors plugged in before the arms are attached as it is easier for assembly. One does need to be careful not to damage the wires for the ESCs during assembly. The figure below shows the side view with all of the dimensions of the the wire holes. Two tubes will be as shown and two will be mirror images (holes on the left side) to allow for the ESCs to be safe from damage from the props.

The two holes on the end for the motor mount and the pin hole go through the tube while the ESC wire holes is just through one wall. The corners near the pinhole are sanded to keep from rubbing on the 3D print. A cut is made where the wires from the motor go into the tube to keep them from pinching. All of these cuts were performed with either a drill press of a Dremel with an appropriate attachment. The cut for the springs is made so the bent legs of the springs slide in easy without damaging them or the arm itself.

The ESC will be between the two smaller ovals with the wires feeding through the holes on either side. The bullet connectors will then be pulled out of the larger oval for the motor and ESC and then connected. After the rotation of each motor is verified, they will be pushed completely into the hole and taped over with electrical tape. The ESC is also wrapped in electrical tape. The motor mount is fastened with two bolts with a rubber washer and nylon nut on the inside portion of the arm when folded up. This would be the bottom side of the arm in the side view here. The wires from the ESC would run through the tube, around the arm pin, and through a hole in the 3D print to reach the electronics of the quadcopter.

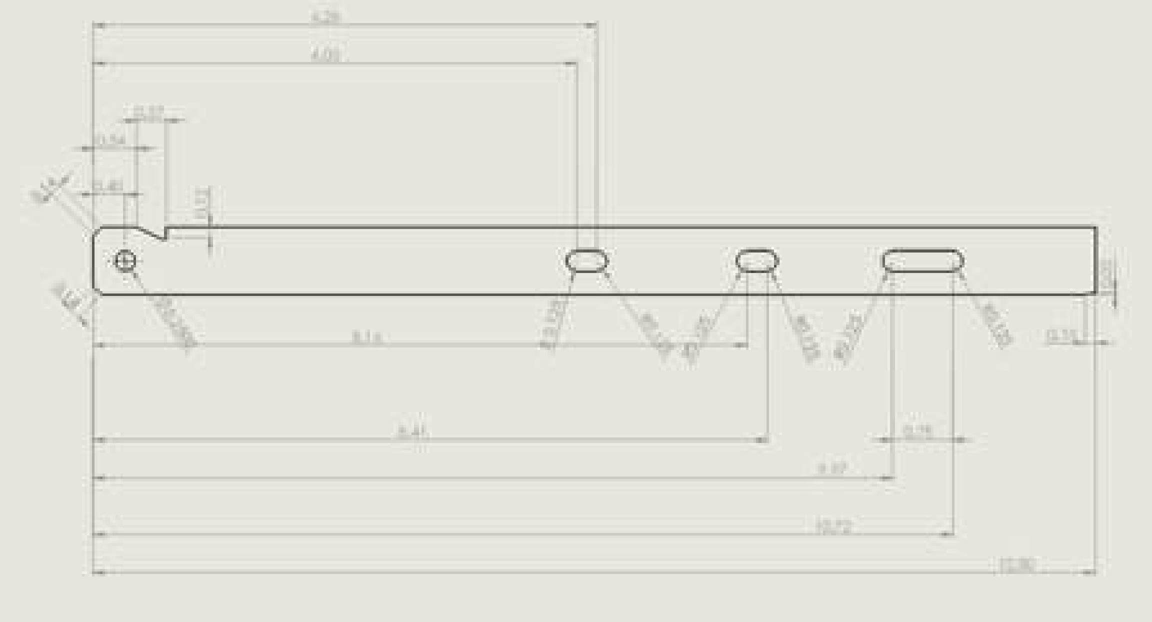


Figure 32. Arm side drawing

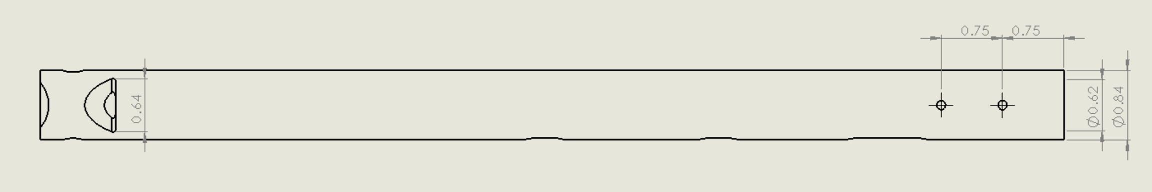


Figure 33. Arm top drawing

The pins that hold the quadcopter are modifies ” bolts. 3” long ones have been cut to 2.6” to allow for a thin nut to attach completely to the end. The threads were filed after the cut to ensure the nut could easily be threaded on. All of the screws that are used on the motor, motor mount and arm have Loctite on them to keep any vibrations from shaking them loose. The Loctite needs 24 hours for full curing. This has been an issue in the past. Medium strength Loctite was used so the nuts could still be removed via hand tools during disassembly.

The parachute system was to be ejected out via a 0.4g charge of black powder. The parachute was folded via the typical rocket parachute method and put inside of the fairings. Tape was added to friction fit the fairings to ensure that it would not slip out on launch or ejections. It was released by the transistor switch that the Avionics Team had created. Refer to the SOLIDWORKS files for more visual information on this.

N. Issues in the Final Design

Some of the major issues with the final design was a rivet shearing issue involved with the bottom section and the mid section. On a test ejection the night before the competition, the piston force sheared the four rivets that held on the bottom section that included the battery. This was resolved for the competition by applying epoxy and aluminum sheet around the edge of the connection and re-drilling the holes. This may also be solved by printing at a higher fill as the bottom section was not printed at 100% infill. But as the prints took over a day to complete, that was not an option for us.

Another issue was the weight of the quadcopter. We did manage to keep the total weight under 7000g, but this was the upper limit of the range of weight we were anticipating. Due to having to use the PVC arms instead of the carbon fiber, adding all of the wires, and all of the other miscellaneous items inside really added up the weight quick. Working to minimize the about of wire used and doing more work to shedding excess weight would be a good next step for the quadcopter in design.

O. Problems with the Backup Parachute

The purpose of the quadcopter parachute was to protect the quadcopter from complete destruction in the worst case scenario as well as mitigate the scary possibility of the quadcopter returning to the ground ballistically. The team decided early in the design process that this would be an important step, because we knew there would be a good chance of losing very expensive avionics equipment in the case that the primary recovery systems fails. Leading up to the competition, the backup parachute had been tested, and the folding and packing methods had been proven effective and reliable. The image below shows one of those tests, and the parachute can be seen clearly to be in the process of unfurling.

Figure 34. Quadcopter parachute test

Once at the Argonia Competition, the Rocket Squad began assembling the quadcopter, and the Avionics Team was following the proper and predetermined procedures to initiate the flight software. During this process, the quadcopter prematurely fired the black powder charge and deployed its parachute. This left the quadcopter unprepared to fly and the entire team baffled. After repeatedly attempting to step through the quadcopter initiation procedures and consistently running into the same premature ejection, the Avionics Team had no solution that allowed the quadcopter to fly with the parachute. This of course brought back the same concerns that lead the team to develop the redundant recovery system in the first place. After a brief group discussion, the team decided to get the opinion of the Range Safety Officer who cleared the quadcopter to fly without the backup parachute. Although this final launch configuration was not as designed, the removal of the backup parachute did not affect the ability of the primary recovery system from doing the mission as designed. Consequently, the quadcopter was launched without the backup parachute. The quadcopter did crash as feared, but fortunately the avionics were not a total loss. Although the quadcopter didn't have the parachute for this launch, there is no guarantee that it would have even been able to save the quadcopter due to the Pixhawk blackout during the flight.

P. The Crash and Hopeful Indicators

Once it was obvious to the Rocket Squad that the quadcopter had crashed somewhere east of the launchpad, the search began. Below is a view of how the pieces of the wreckage were found.

Figure 35. Post-crash quadcopter

Upon initial inspection, it was clear that the avionics were intact and that the quadcopter was in one piece before impact. All four quadcopter arms were present, and only one motor mount had broken. The motor mount that had broken was still firmly attached to the motor, and both were slightly barred in what appeared to be the impact crater. The explanation to the evidence found is that the motor mount broke only during impact, and it is reasonable to believe that the arm belonging to the broken motor mount was first to strike the ground. Despite the violent impact, it is surprising to find that not a single propeller blade was broken, and only one was missing and never ended up being found. That missing propeller blade is the only piece of quadcopter hardware which what not at the impact site, and that is what the integration team believes that the loss of a prop during flight was a major cause in the recovery system failure.

Q. The Missing Propeller

The integration team blames the loss of a propeller as a leading cause of the loss of the quadcopter, but why it came loose is the more important area of focus. Prior to launch, the Integration Team placed Locktite on every screw on the quadcopter except the ones securing the propellers to the motors, and this was out of fear that the propellers would get stuck and no longer have the ability to fold and unfurl. It is worth noting that none of the bolts with Locktite came loose. Upon further analysis, it was found that the holes in which the propellers screwed into were almost completely sheared out, and this included the one with the missing propeller. This explains how the screw could have come out during such a short flight. Below is a photo of the sheared out screw hole. The shearing is not obvious in the photo, but there is a significant amount of noticeable wear and tear.

Figure 36. Stripped motor propeller hole

The one positive way to think about this failure is that the propeller most likely came off due to the motor spinning. This is significant, because due to the Pixhawk blackout, the team has spotty information about the quadcopter while in the air. The fact that the quadcopter was fully intact before impact points to the fact that the quadcopter ejection was a success, and the propeller falling off is further evidence that the quadcopter was trying to fly. Furthermore, there are impact marks on the tape on the quadcopter arms, and this looked just like what we saw during testing when the propellers came in contact with the arms. This fact gives the team confidence that the motors were under power and attempting to fly prior to impact. Despite the mission failure in the end, the successes of the flight at Argonia cannot be understated, and these conclusions drawn from the evidence observed in the wreckage speak to what success there was.

R. Where to go Next/Lessons Learned

Some of the major things learned throughout this process are to devote more time to prototyping than anticipated. Due to long shipping and printing waits, it took longer to get through prototypes than we anticipated. Pushing for a more accelerated time line would be a good choice for other teams working for this competition. Another thing to consider is the characteristics of the materials you are using in testing and the real-deal. While the carbon fiber arms sounded great, they cracked extremely easy and were not easy to manufacture. It just goes to show that just because something is known for its immense strength, it does not mean it is the best option. The cheaper PVC worked better because it was tougher and more resilient to the testing process and ultimately was chosen to be the material for the arms in the final quadcopter. This is also shown with the 3D printing materials. We chose to stick with PLA even though it was the weakest option because it still did the job right. The SLA shattered when it failed and Nylon was extremely expensive. Do not always go for "The Best", go for what fits your application. Another lesson learned is to have backup after backup. Many of our backups failed throughout the design and competition. The ability to just replace something if it broke was very useful to the team. A spare set of every single component on the quadcopter was available which allowed for less risk when assembling as if something broke it would not ruin the system. It could be replaced.

From this point, the design needs to be tested more. The one thing missing from this design process was more intensive testing, which was not available to us. Not being able to launch the actual system prior to the competition led to many unknowns that we could just not account for. Therefore, one of the necessities of another team tackling this project is to find a place where they could launch before the competition to test their system. This may be at the Unmanned Airfield, at Argonia, or at a Space Port, depending on where is available.

V. Avionics

A. Components

In order to quickly achieve this goal, the avionics team had to work with off-the-shelf components for the flight computer and motors of the quadcopter. In order to do this we developed a system that would use a Raspberry Pi in conjunction with a Pixhawk 2.1 to autonomously engage and fly a preset mission to a predetermined location after deploying from the rocket. The critical aspect of this was choosing the appropriate off-the-shelf motor, ESCs, and battery to successfully fly and recover the quad from beyond 8,000' AGL and 5,000' horizontally. To do this, we used an online calculator called eCalc that analyzed hover flight times and a number of other quadcopter characteristics with the off-the-shelf components. This is how we chose a 4000 mAh battery, 30A ESCs, and the Multistar Elite 4114-330 motors for the quadcopter. The results are shown in the figures below.

General
Model Weight: 2700 g incl. Drive / 95.2 oz
# of Rotors: 4 flat
Frame Size: 863.6 mm / 34 inch
FCU Tilt Limit: no limit
Field Elevation: 305 m ASL / 1001 ft ASL
Air Temperature: 25 °C / 77 °F
Pressure (QNH): 1013 hPa / 29.91 inHg

Battery Cell
Type (Cont. / max. C) - charge state: LiPo 4000mAh - 25/35C - normal
Configuration: 6 S 1 P
Cell Capacity: 4000 mAh / 4000 mAh total
max. discharge: 80%
Resistance: 0.0053 Ohm
Voltage: 3.7 V
C-Rate: 25 C cont. / 35 C max
Weight: 99 g / 3.5 oz

Controller
Type: max 30A
Current: 30 A cont. / 30 A max
Resistance: 0.008 Ohm
Weight: 40 g / 1.4 oz
Accessories
Current drain: 0 A
Weight: 0 g / 0 oz

Motor
Manufacturer - Type (Kv) - Cooling: MultiStar - Elite 4114-330 (330) - good
KV (w/o torque): 330 rpm/V
no-load Current: 0.73 A @ 10 V
Limit (up to 15s): 500 W
Resistance: 0.15 Ohm
Case Length: 32.5 mm / 1.28 inch
mag. Poles: 22
Weight: 152 g / 5.4 oz

Propeller
Type - yoke twist: custom - 0°
Diameter: 15.5 inch / 393.7 mm
Pitch: 5.2 inch / 132.1 mm
Blades: 2
PConst / TConst: 1.2 / 1.0
Gear Ratio: 1 : 1

Load: 15.86
Hover Flight Time: 12
electric Power: 318
est. Temperature: 48
Thrust-Weight: 2.3
specific Thrust: 7.78
Configuration

Remarks:

Battery		
Load:	15.86	C
Voltage:	20.18	V
Rated Voltage:	22.20	V
Energy:	88.8	Wh
Total Capacity:	4000	mAh
Used Capacity:	3200	mAh
min. Flight Time:	3.0	min
Mixed Flight Time:	8.4	min
Hover Flight Time:	12.0	min
Weight:	594	g
	21	oz

Motor @ Optimum Efficiency		
Current:	11.80	A
Voltage:	20.60	V
Revolutions*:	6165	rpm
electric Power:	243.2	W
mech. Power:	200.7	W
Efficiency:	82.5	%

Motor @ Maximum		
Current:	15.86	A
Voltage:	20.06	V
Revolutions*:	5766	rpm
electric Power:	318.0	W
mech. Power:	259.6	W
Power-Weight:	471.2	W/kg
	213.7	W/lb
Efficiency:	81.6	%
est. Temperature:	48	°C
	118	°F
Wattmeter readings		
Current:	63.44	A
Voltage:	20.18	V
Power:	1280.2	W

Motor @ Hover		
Current:	4.01	A
Voltage:	21.66	V
Revolutions*:	3320	rpm
Throttle (log):	40	%
Throttle (linear):	52	%
electric Power:	86.8	W
mech. Power:	69.8	W
Power-Weight:	131.8	W/kg
	59.8	W/lb
Efficiency:	80.4	%
est. Temperature:	32	°C
	90	°F
specific Thrust:	7.78	g/W
	0.27	oz/W

Total Drive		
Drive Weight:	1498	g
	52.8	oz
Thrust-Weight:	2.3	: 1
Current @ Hover:	16.03	A
P(in) @ Hover:	355.9	W
P(out) @ Hover:	279.3	W
Efficiency @ Hover:	78.5	%
Current @ max:	63.43	A
P(in) @ max:	1408.1	W
P(out) @ max:	1038.5	W
Efficiency @ max:	73.7	%

Multicopter		
All-up Weight:	2700	g
	95.2	oz
add. Payload:	2744	g
	96.8	oz
max Tilt:	60	°
max. Speed:	32	km/h
	19.9	mph
est. rate of climb:	5.7	m/s
	1122	ft/min
Total Disc Area:	48.69	dm²
	754.7	in²
with Rotor fail:	☒	

Figure 37. Ecalc quadcopter analysis

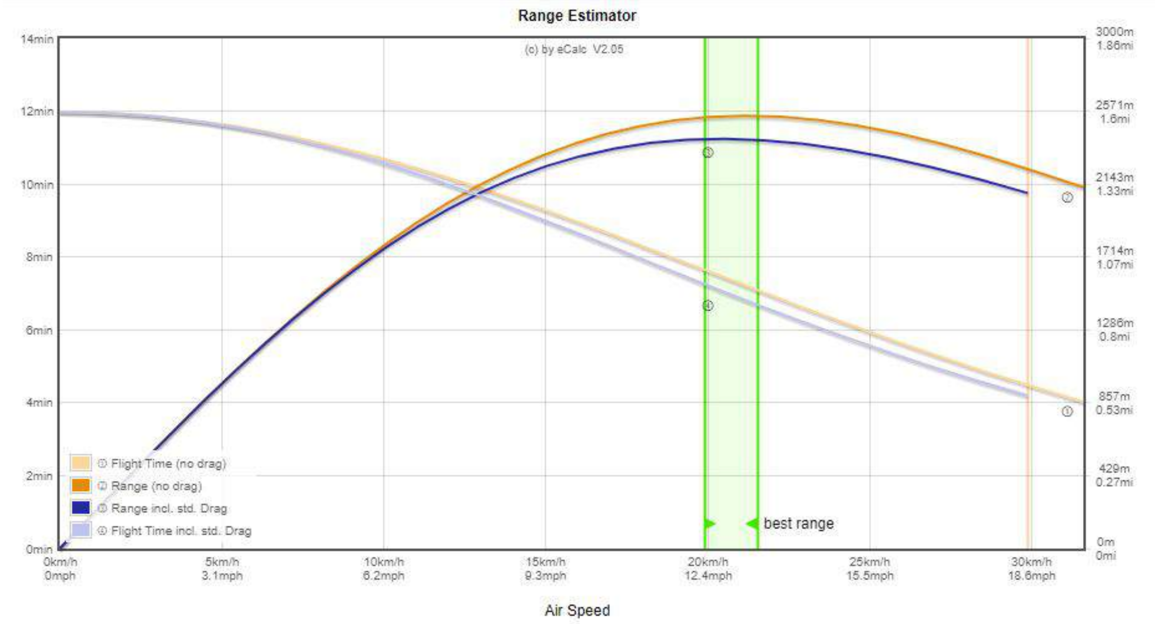


Figure 38. Ecalc quadcopter analysis

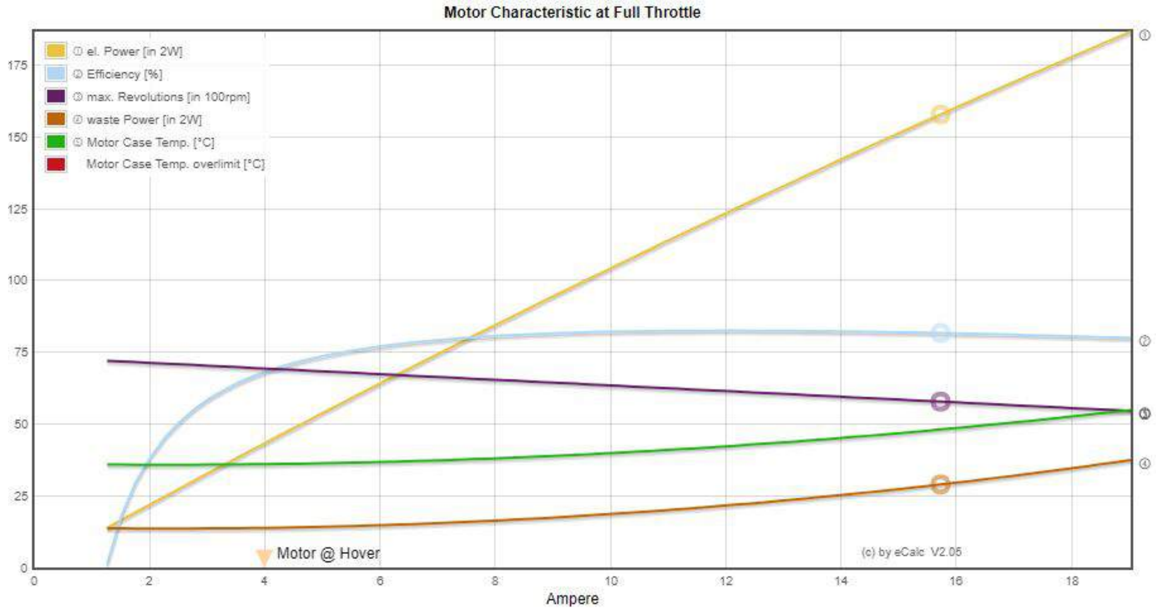


Figure 39. Ecalc quadcopter analysis

B. Light Sensor

A major challenge faced in the design of our quadcopter was when to initialize the flight program. An initial idea was to use an accelerometer to detect the black powder separation event. It was decided this wouldn't work; however, because there is a chance that the charge could go off without the quad being ejected. Such an even could damage the quad hindering the chances of another launch occurring. Another idea we had was to use an ultrasonic range finder positioned on the bottom of the quad. It was ultimately decided this wouldn't work for two reasons. One, since the folded quad arms did not provide a solid perpendicular surface to poll, we were afraid the readings would be inconsistent. The other reason was that an ultrasonic range finder is essentially a speaker that outputs a sound and listens for a response. Since a rocket launch is a high vibration environment with changing air pressures, we were unsure of if these variables would affect the operation of the sensor. This led us to ultimately choose to use a light sensor on the side of the quad facing the wall of the rocket because a light sensor would provide the best indicator of the quad coming out of the rocket.

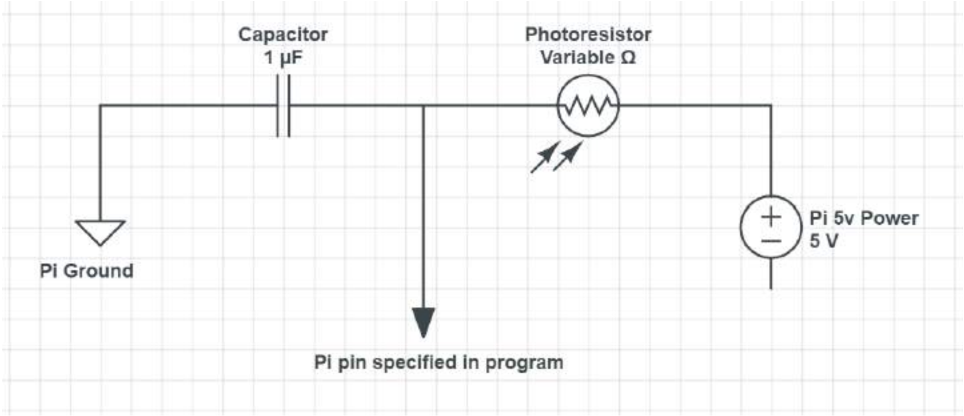


Figure 40. Light sensor circuit

We ended up using two light sensors positioned on the side of the quad. This provided redundancy in case one of them lost connection. A circuit was constructed consisting of power coming from the pi, going through a photo resistor, and then charging a capacitor. There would also be a pin from the pi connected in the middle constantly reading the charge state of the capacitor. The code was constructed in such a way that a timer would run, wait for the pin that is connected into the circuit to read high indicating the capacitor was charged, and then the capacitor would be reset and the process would start over. A full charge cycle would take about 5-10 processor cycles in sunlight, and was capped at 5000 cycles when in the tube. This cap was needed because it was so dark that it would take too long for the capacitor to charge. This parity between light and dark was large enough to make it easy to tell when if the quad was ejected or not. Attached below is a diagram of the circuit.

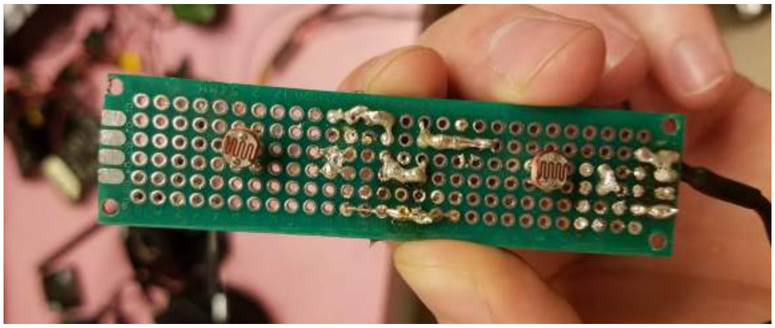


Figure 41. Front of circuit board

As mentioned above, redundant light sensors were used. Initially we just ran wires directly to the components and soldered them together, but after complications with them coming apart in the first test launch we decided to make it more rugged. To accomplish this, we ordered circuit boards off of amazon. This allowed the circuit to be soldered onto a rigid body making it more resistant to wires being tugged on. The board we chose also had the added bonus on having screw holes in it so we could solidly attached the light sensors to the quad body without using epoxy. This allowed for more flexibility in making repairs. Finally, once everything on the board was soldered and tested we coated all components and joints in hot glue for extra reinforcement. Pictures of the circuit may be seen below.

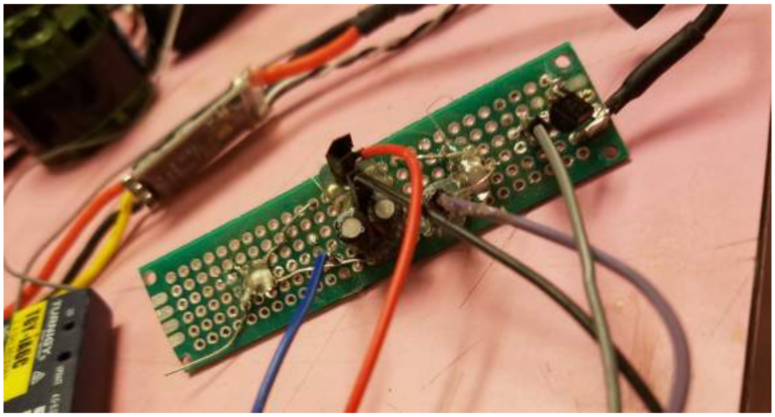


Figure 42. Back of circuit board

C. Parachute Circuit

The parachute circuit is relatively simple. It can be seen in the pictures above and diagram below. Essentially the positive side of the battery is connected to one side of the black powder ignitor. We chose to use alligator clips for the so it could be easily hooked up on the field without needing to solder. The other side of the ignitor is then connected to the collector side of the transistor. The transmitter side of the transistor is then wired to the negative side of the battery (not the pi ground). Finally, the center pin, or base pin, of the transistor is connected to whatever pin will be used to actuate the transistor. All that's needed is for this pin to be set to high and the circuit will complete blowing the ignitor. A diagram of the circuit can be seen below.

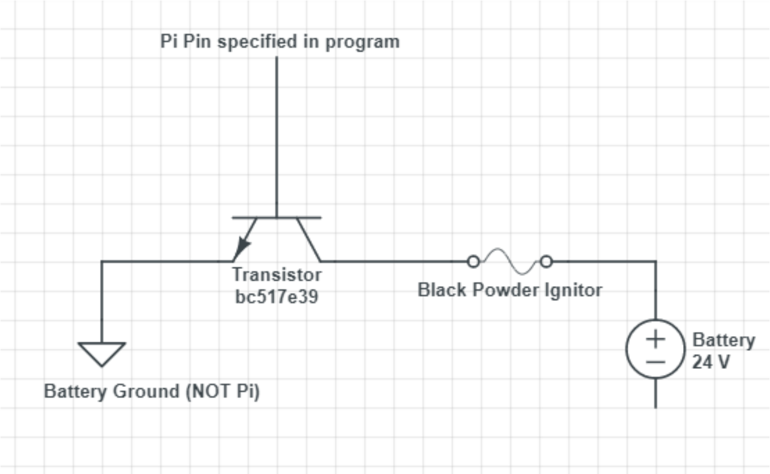


Figure 43. Parachute circuit

D. Quadcopter Stability

The goal of testing the stability of the quadcopter was to determine if it would be capable of catching itself after ejection from the rocket at apogee. During the design phase, the question arose as to whether it would be easier to have the quad attached to a sled to allow for a more controlled deployment or if it would even be capable of catching itself in flight. This is an issue of flight hardware more than anything else. Research showed that for the Pixhawk family of flight controllers there is a mode called "Throw Mode" that allows the user to arm the quadcopter then throw it into the air. Once the quadcopter reaches its apogee it will spin up the propellers and catch itself mid-air. We wanted to verify this for ourselves so we used a standard 3DR Iris+ and used throw mode to see how the quadcopter would catch itself. First we attempted throwing it right-side up, then upside down, then upside down and spinning. Each time the quadcopter caught itself in just a few feet therefore proving that the flight hardware had the appropriate PID system to accomplish this mission.

Figure 44. Iris+ in THROW Mode

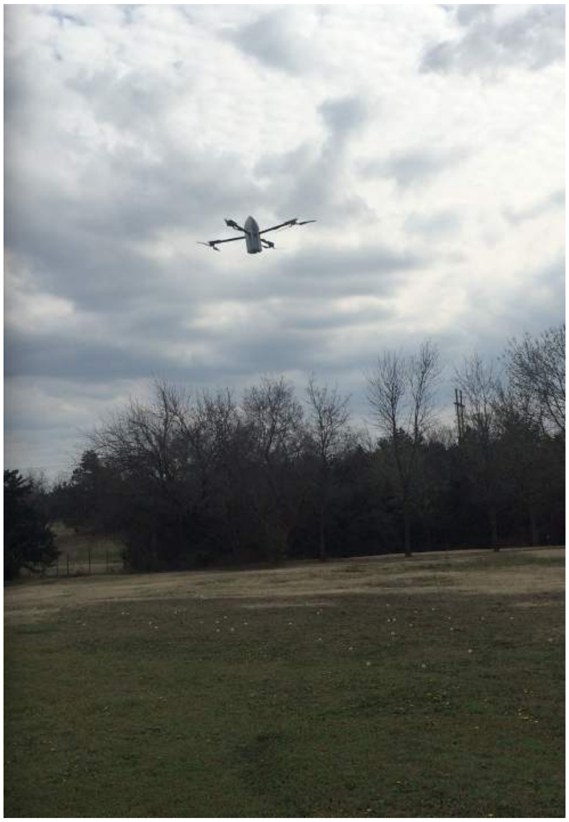
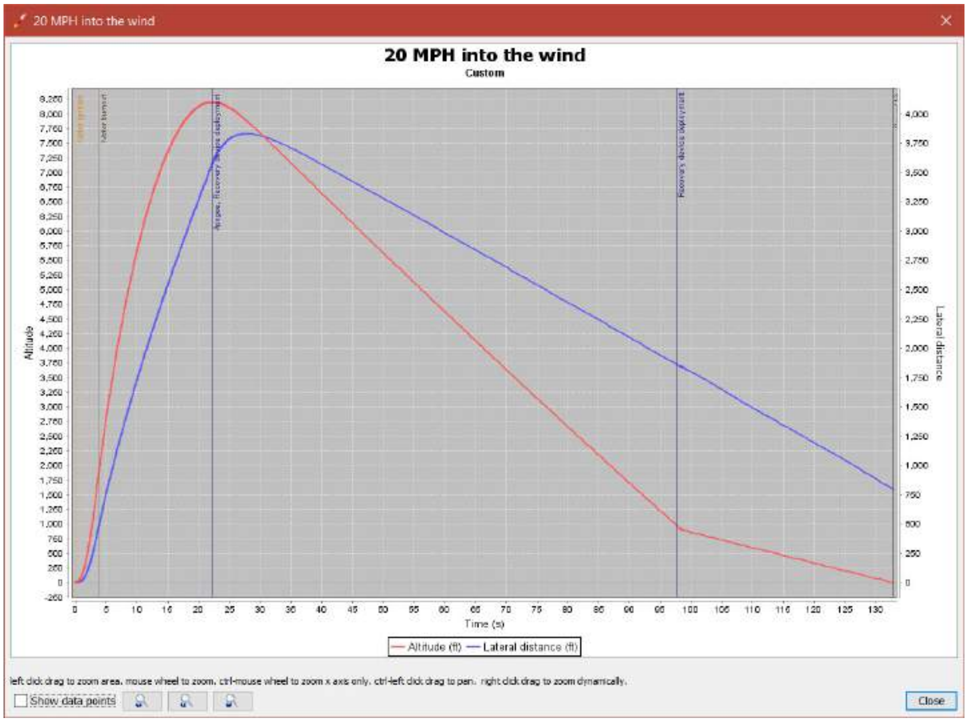


Figure 45. Quadcopter Free Fall Test

This was a greater challenge to test with our quadcopter due to the increase in size and therefore overall risk. We discussed a number of ways to do this, including the original plan of just shaking the quadcopter and then throwing it into the air. Due to the difficulty of getting the quadcopter high enough into the air to catch itself, we devised another plan. The process of the eventual testing was to fly the quadcopter up to around fifty feet AGL and then switch into Stabilize Mode. This would allow for the motors to shutdown when the throttle was cut to zero. A second after the throttle was cut and the quadcopter was in a free fall, the quadcopter would be switched into AUTO Mode and ideally the system would be able to catch itself and proceed to carry out its mission. During testing we had already pushed the quadcopter to its limits and the arms were beginning to break. The result of this test is that when the quadcopter attempted to correct itself, the force from the motors proved to be too much for the cracking carbon fiber and therefore the arms broke and caused the quadcopter to fall. It was encouraging though that the system seemed to recognize what was happening and attempt to stabilize and carry out the mission. If there had been more time to test this process, we believe that it would have worked as expected.

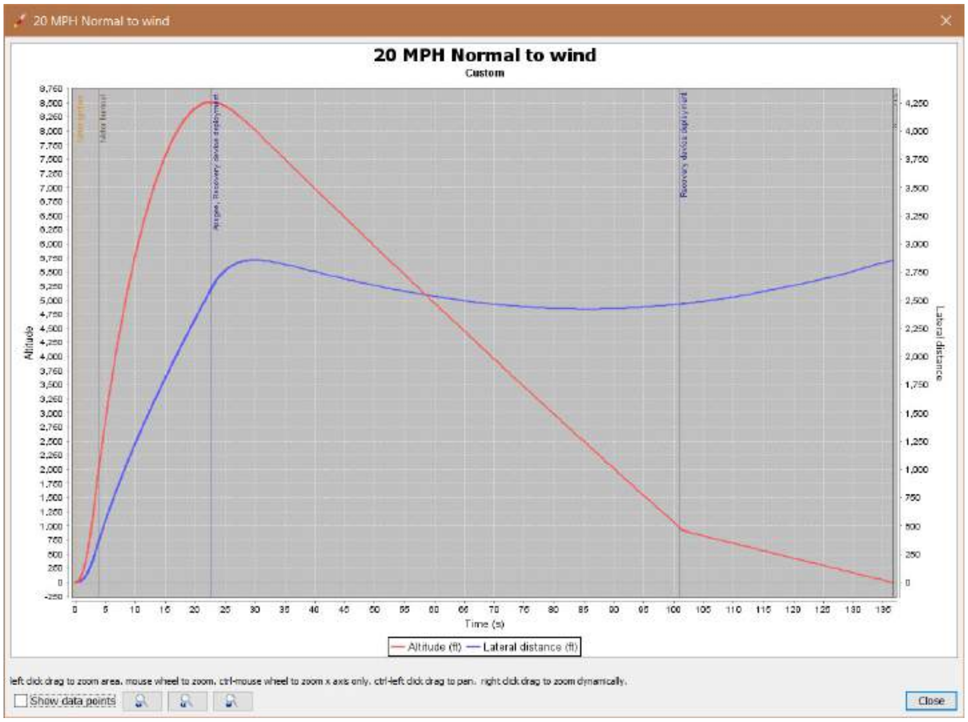
E. Rocket Wind Drift

When designing the quadcopter, we needed to ensure it was robust enough to fly in any condition that could be launched in. Part of this was determining the maximum distance it would have to fly under worst case wind scenarios. To figure this out, we took our OpenRocket model and changed the simulation conditions to include 20 MPH winds. Additionally, we wan the simulation 3 times with the rocket launching at the maximum allowed inclination of 83 degrees from the ground into the wind, with the wind, and normal to the wind. The results of these simulations can be seen below. Next we determined that the most efficient path for the quad to return would be on a horizontal trajectory from where it recovers midair. To find the longest distance, we looked at both the altitude the rocket was able to reach, and the distance it weather cocked to the side and calculated the hypotenuse. Surprisingly, we found the worst case scenario for distance traveled to be launching into the wind. This is because as the rocket is ascending, the wind pushes the fins and causes the rocket to rotate closer to a horizontal trajectory. That is also why there is a loss in altitude with that scenario. An advantage to this launch case however is that the quad gets to use the wind to be blown back to the launch site instead of fighting it. The next worse was launching normal to the wind. Even though there was less lateral drift, the higher achieved altitude makes the path home only slightly less far than launching directly into the wind. In the end this is really the worst case scenario because while there is less distance to fly than launching into the wind, the quad will be fighting against the wind all the way back. Launching with the wind had by far the least absolute effect on lateral drift. The combination of the rocket initially lunching with the wind then turning into it caused the weather cocking effect to nearly cancel itself out. This led to little lateral drift, but the quadcopter would still need to fight the wind as it ascended. In the end, these simulations are only as accurate as the numbers used to calculate them. Unfortunately, OpenRocket uses one singular wind speed and wind direction all the way to apogee. This does not accurately model a real launch due to wind direction and speed possibly changing in so little as 500'. There exists other software that can run monte carlo simulations using up to 20 wind layers that may prove to be more accurate, however it costs $1,000 and can only be used by US citizens due to ITAR. The name of the software is ROCKSIM Pro.



left click drag to zoom area. mouse wheel to zoom. ctrl-mouse wheel to zoom x axis only. ctrl-left click drag to pan. right click drag to zoom dynamically.

Figure 46. 20 MPH Into Wind



left click drag to zoom area. mouse wheel to zoom. ctrl-mouse wheel to zoom x axis only. ctrl-left click drag to pan. right click drag to zoom dynamically.

Figure 47. 20 MPH Normal to Wind

left click drag to zoom area. mouse wheel to zoom. ctrl-mouse wheel to zoom x axis only. ctrl-left click drag to pan. right click drag to zoom dynamically.

Figure 48. 20 MPH with the Wind

F. Telemetry Range and Avionics Vibration Verification

Testing the range of our telemetry and the how vibrations affect our avionics were extremely important to the overall success of our system. We used our second flight test in order to test both of these issues. This was the launch of the first full body prototype with spring loaded arms and a Pixhawk with a telemetry radio inside. In order to say that the system was verified, we would need to keep telemetry connection beyond 8,000' and not have any major errors from the flight controller.

1. Range Verification Results

Overall, this second rocket was predicted to go higher than we were anticipating our final design to go, approximately 9,500'. Therefore, it allowed us to test telemetry to an altitude beyond what would be required on the day of launch. The on-board radio was placed in the same location as it would be during the official flight and the ground control radio was placed at the launch table approximately 500' away from the pad. Telemetry was successfully kept past apogee and was only lost due to separation issues that disconnected the nose cone from the body during flight and therefore disconnected the telemetry radio from the Pixhawk. However, this test did prove that we would not have connection issues based on range during the official flight.

2. Vibration Verification Results

There are three major events that occur during flight that cause all the avionics to experience extreme conditions. These are the high G environment created at launch, the vibrations produced during motor burn, and the high G environment created form the ejection at apogee. This was a large concern for us since, the hardware was COTS and was only designed for vibrations produced during normal quadcopter operations, not rocket operations. From research, we believed that the Pixhawk should not have any issues with these events due to other projects launching this hardware. However, it was still verified during the launch since all data remained accurate without any major errors or issues.

3. Post Launch Failure Analysis Results - Vibration Theory

During the final launch, everything worked according to plan up until a few seconds after apogee. At this point the light sensors had indicated to the Pixhawk that the quad was outside of the rocket and it was ready to engage its autonomous mission. The motors and propellers began to spin up and then all data from the Pixhawk froze. This was not a telemetry problem as after flight analysis would show that the data logged on the Pixhawk also stopped at this time. The Pixhawk continued to communicate with the Raspberry Pi throughout this time of frozen data and it would appear that the quad continued to attempt to fly due to the crash occurring approximately 80 seconds after launch. If the quadcopter had gone ballistic out of the rocket then it would have crashed 50 seconds after launch. The true reason for this error is still unknown, however it could be rooted in a high G load environment paired with the Pixhawk attempting to stabilize the quadcopter after deployment. It may have been too much for the Pixhawk to handle and therefore freeze.

G. Software

The flight control was handled by a COTS Pixhawk flight control board. However, the Pixhawk could not run scripts locally and instead we used a Raspberry Pi 3 to process data and send commands to the Pixhawk. The commands were sent with through the serial connection via the MAVlink protocol. The MAVLink protocol is the standard for transmitting information from a ground station to the vehicle and vice-versa. The MAVLink session broadcasts data to all connected entities and utilizes a "heartbeat" packet to verify connection. Not only was this natively built into the Pixhawk and ground control software, it allowed us to monitor telemetry, and use and onboard computer to autonomously navigate. We utilized the Pi running a Linux distro (Raspbian Sketch) as a pseudo onboard control station to read and issue commands as necessary. MAVProxy is the tool of choice to configure a lightweight on-board control station. While the actual communication protocol can be quite complex, this was simplified by using the DroneKit python library. DroneKit was developed to establish a MAVProxy session and connect via MAVLink to read vehicle data and send commands to the aircraft from the onboard Raspberry Pi. In essence, DroneKit is simply a python wrapper for MAVLink running on top of the MAVProxy session.

Testing indicated that the Pixhawk flight control algorithms were capable of correcting and stabilizing the vehicle in the chaotic ejection phase as well as navigating the drone to a predetermined landing site after being given the GPS coordinates. In house software would need to handle pre-arming procedures, detecting the deployment of the quad, and power loss scenarios.

One of the main issues faced was power loss during flight. Using the crontab feature of the Linux distro, the script would be run on reboot after the operating system booted up. Next the program would detect which phase of flight the vehicle was in by looking if certain files had been created. For example, after calibration was finished a .flag file would be created that would signal the program to proceed to the next step if an in-flight reboot occurred. Similar files were created to indicate if the quad had been armed and awaiting deployment, or if the quad was already deployed. These files would be manually removed after each test. Each test would also create a flight log to troubleshoot any issues.

Pre-arming procedures included calibration of sensors and gyros as well as setting the home location for autonomous landing. During this phase it was important that all communication and commands be disabled while we were handling the drone. It was also important that the drone remained powered on so that it does not loose calibration. After the quad was initialized and in the rocket tube, the quad would be armed by switching flight modes from the radio controller. It would then signal that it was armed and ready for takeoff by disarming and rearming the quad motors. This provided a audible queue to bystanders.

The quad used light sensors to detect the deployment of the vehicle out of the main rocket tube. Since the Raspberry Pi does not have analog inputs to read values directly from the photoresistors, a capacitor was used to in series with the photo resistor to charge up until a high signal was read on a digital pin. This meant the pi timed how long it took until the capacitor was charged. The longer the time, the darker the reading. Additionally, a time out was implemented should the light sensor become disconnected in flight. To add redundancy, two light sensors were used and 5 successive positive values must be read before the vehicle had determined it was deployed.

Once the quad was deployed, the Pi would switch the aircraft into AUTO mode. This would then stabilize the aircraft and return the quad to the landing site. If all went correctly, the vehicle would navigate to the landing site without any guidance or assistance. Concurrently the Pi would be listening for a manual override signal from the radio controller. If STABILIZE mode was engaged, the Pi allow for manual override and would no longer send commands to the vehicle in an effort to avoid confusion from simultaneous signals. Throughout the flight duration the Pi would be monitoring the altitude and vertical speed. If the aircraft dropped below a certain altitude threshold traveling faster than 30 fps downward, it would indicate that the quad was unstable and/or ballistic. In the event of a ballistic reentry, the pi would stop all motors and deploy a reserve parachute via a small explosive charge activated through the GPIO pins on the pi. The reserve parachute could also be triggered manually from the radio controller via a mode change. NOTE: the reserve parachute was disabled during final flight, as it was found that a reboot during flight would inadvertently trigger the charge as all GPIO pins were pulsed high on boot.

These methods were tested individually by simulating deployment, rapid downward velocity, and chaotic orientations. The quad was lowered from altitude to simulate altitude and velocity change and ejected from the tube to simulate deployment deployment. In all scenarios, the software correctly detected the event and took the appropriate next steps. The software treats the vehicle as a point entity so all commands and sensor readings are in reference to the NED frame. This simplified testing, as all velocities were the same regardless of vehicle attitude.

VI. Rocket Wraps

At the end of the manufacturing process for most rockets, they usually get dolled up by spray paint or other coloring methods. However, this year Rocket Squad wanted to make the rockets look top notch and by wrapping them, they were able to make the rockets look exactly the way they envisioned. Wrapping the rocket not only provides the ability to make the rocket look exactly how the team wants, it is also slightly more aerodynamic and a much easier and quicker process than painting. Wrapping the rockets can save ample amount of valuable time and allow that time to be spent on other significant areas.

The process of wrapping the rockets begins by designing and inserting exactly what is desired into any computer designing software. Below is an example of how the process started for Rocket Squad's The Other Things. This design was created in Adobe Photshop CC 2017. The canvas was created with the dimensions of rocket (outer circumference and height).

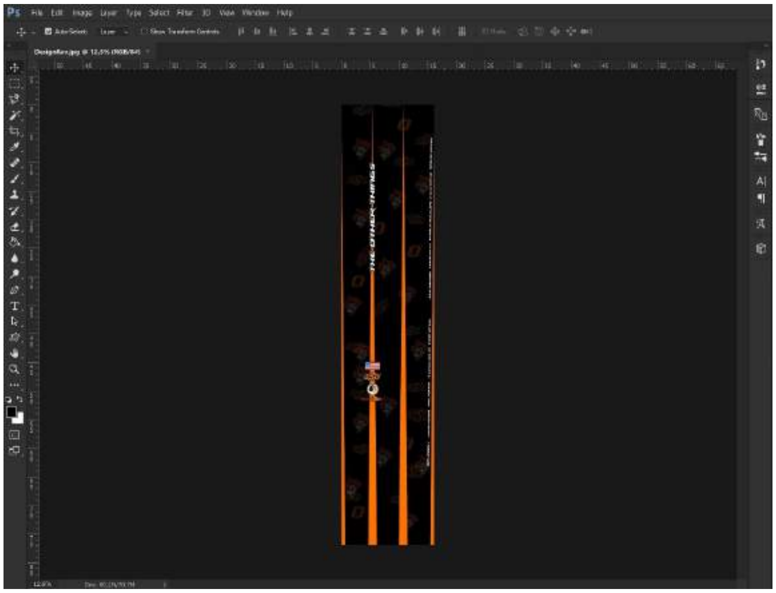


Figure 49. ***The Other Things* in Photoshop**

Once the design is agreed upon with all teammates, it is sent to a local graphic design and digital print shop. For Rocket Squad, Edge Grafix in Tulsa, Oklahoma was selected to do all the teams printing. This is a locally owned and operated business that establishes a wonderful connection with the customer and can understand and print exactly what the customer is wanting/needing.

When the final design is printed, it appears as one very big sticker. However, the wrap material used by Edge Grafix breathes through the laminate layer and makes the install and appearance significantly nicer. In the picture below, the final print can be seen for a rocket that was wrapped for the Oklahoma State University Rocketry Team this semester, *Results May Vary*.

Figure 50. Wrapping Preparation

Next up after the print is finished, the install process begins. This is easily the most tedious part of the entire job. Ensuring that the rocket surface is clean from any dust and foreign object debris is very crucial and makes the install much easier. Even though the material can breathe and wrap around minor defects, a smooth surface is optimal and ideal for the wrap. The install begins by lining up the wrap exactly how it was envisioned to go on the rocket. Once everything appears to be lined up correctly and in the right spot, simply peel back the wrap and apply with a rubber squeegee.

Figure 51. Rubber Squeegee

A heat gun can be very helpful once the wrap is applied to ensure that the adhesive is attracted to the rocket surface. A heat gun will also help to settle air bubbles and wrinkles that might be seen. However, caution needs to be taken when using a heat gun with the wrap material. It can melt and destroy the wrap very easily. It can be the installers best friend or worst nightmare.

Figure 52. Heat Gun

When the wrap is completely installed and appears to be stuck down everywhere on the rocket with no wrinkles or bubbles, trimming the edges is the next step. This can be done with an X-Acto knife. It is important to trim the edges and make the necessary cuts on the wrap to ensure that there is no unwanted lifting of the wrap at the seems and edges.

Figure 53. X-Acto

After the entire install is complete, the rocket should look exactly how is was designed in the computer designing software. Below is a picture of some rockets that were wrapped for Rocket Squad and the Oklahoma State University Rocketry Team this semester.

Figure 54. Wrapped Rockets

VII. Drawing List

1. Final Assembly
    (a) Quad Bottom
        i. Chute Fairing Left
        ii. Chute Fairing Right
    (b) Quad Mid
        i. Quad Arm LH
            A. Fiberglass Quad Arm Motor Mount
        ii. Quad Arm RH
            A. Fiberglass Quad Arm Motor Mount
    (c) Quad Top
        i. Electronics Plate Level 1
        ii. Electronics Plate Level 2
        iii. Electronics Plate Level 3
        iv. Electronics Plate Level 4

VIII. Full Documentation

All information for this project can be found in the ”Speedier Fest” folder given to Dane Johnson (dane.johnson@okstate.edu) and Dr. Jamey Jacob (jdjacob@okstate.edu) at USRI.