Two-Stage Rocket Fail-Safe System

UCI Rocket Project

Aerodynamics and Manufacture Engineer: Brandon Hernaez
Systems and Fail-Safe Engineer: Yuan Zhang
Advisors: Prof. Kenneth Mease, Dave McCue

University of California, Irvine

2nd Iteration

October 12, 2015

Contents

Part 1 (Prepared by Brandon Hernaez) 3

Objective 3
Introduction 3
Motivation 3
Series vs. Parallel 3
Motor Selection 4
Airframe Design 5
Barrowman Equations 5
Center of Gravity 8
Design 9
Fabrication 11
Pre-Launch Procedures 13
Problems before Launch 16
The Launch 17
Failure Analysis Part 1 17
2nd Chance Part 1 18
Results and Estimations 24

Part 2 (Prepared by Yuan Zhang) 26

Final Fail-Safe System Design 26
Abandoned Design 28
Schematic 29
Avionics Fabrication 30
Fail-Safe System Logic 35
Flow Chart 36
Pre-Launch Test 37
Launch Analysis 37
Flight Data and Videos 38
Failure Analysis Part 2 41
Failure Analysis of IMU 50
2nd Chance Part 2 52

Appendix 59

Part 1 (Prepared by Brandon Hernaez)

Objective

Design a fail-safe system that monitors the orientation of the upper stage during separation. The purpose of this detection system is to control whether or not the second stage should be ignited. The failsafe system will also monitor and check that separation has been fully achieved. The costeffectiveness is a key factor as we aim to deliver a detection mechanism that works for very low cost and easy to build.

Introduction

In large scale amateur rocketry, multi-stage rockets are especially difficult to build and are frequent to fail. Many enthusiasts often use solid rocket engines in a single stage configuration to either enjoy the hobby or further atmospheric research. For two or more stages, rocket motors are either stacked in series or put side by side in parallel. The benefit of a multi-stage rocket is the mid-flight weight shedding and fresh propellant that is carried with it. The overall height is increased and the cost for propellant to achieve that height decreases (if, otherwise, a single stage is implemented).

Motivation

The worry when launching these rockets comes from the separation phase. For every rocket used for high altitude goals, reusability decreases, so new vehicles are built and rebuilt. There is no easy was to make sure that a stage will separate smoothly. Ground separation tests will show that the stages separate but it will not show that the upper stage remains in a constant orientation. Aerodynamic factors are the unforeseeable detriments. As one body separates, any perturbation on the upper stage will not be corrected for and cause it to stray from the desired flight path. Active control systems would have to be implemented to overcome this but that is not the scope of the project. Active control systems are not easily made and implemented for the average rocketeer. This failsafe system aims to save the upper stage from wasting an engine if the course is ruined during separation. For Level 3 rocket motors, a single reload can cost $700 and up for an M size motor. It would be very favorable if the engine is used in a straight vertical shot rather than an orientation tilted 10 degrees with the earth’s surface.

Series vs. Parallel

A rocket in series will have significantly less drag than a paralleled multi-stage vehicle and will have less issues with separating the center of gravity, CG, from the center of Pressure, CP. The parallel rocket configuration will usually have a cluster of booster engines attached evenly around the main body, causing the CG to be pulled down towards the back of the rocket. This causes issues with weight as the fins on the rocket will need to be larger to keep the rocket stable. To increase fin size means to increase thickness and reinforce areas they are attached which adds weight. For a series rocket configuration, it is easier to spread the weight throughout the body. However, an issue with stabilization comes up when the initial rocket configuration causes the upper stage fins to act as subsonic canards. Also, the upper stage fins can disturb the flow downstream for the main booster fins.

The Series configuration was selected due to the reduction in drag and the type if separation method we wanted to implement. The common 2 stage separation mode was a sleeve fit, this type of connection between the two stages is easy to fabricate but it is unknown if it is the typical choice for 2 stage rocket designers. The reduction in drag allows cheaper solid propellant reloads to be used. This allows for lighter propellant casings and overall weight to be reduced.

Motor Selection

The motor was chosen with budget, vehicle diameter, viewable height, and thrust output in mind. Looking at the Apogeerockets website, motors are listed with various specifications of interest. The outer diameter of the rocket was settled to be a continuous 4”. The Possible motor diameters are 24mm, 29mm, 38mm, and 54mm. We wanted to have the rocket separate just after the first engine burnout and we wanted it to be in view when that occurred. Since the Rocket was estimated to weigh about 4 to 6 kilograms we needed a thrust output that would be roughly 5 times the weight since various online sources, written by long time hobbyists, claimed that a motor is effective starting at 5 times the initial weight. The 38mm size was the most desirable due to its lower cost, preferable thrust range and size.   Of course this implies that the rocket is built correctly and has decently sized fins.

The motor choices for the 38mm range varied with: Total Impulse, Maximum Thrust, Burn Time, and Average Thrust. The after the 5th design iteration the rocket weight was estimated to be near 5kg. The J350-W was selected as a viable motor.

Table 1: AeroTech J350 Specs. from Thrustcurve.org

J350-W				
Total Impulse	Max. Trust	Burn Time	Average Thrust	Prop Weight
679.1Ns	822.5N	1.5s	445.0N	361g

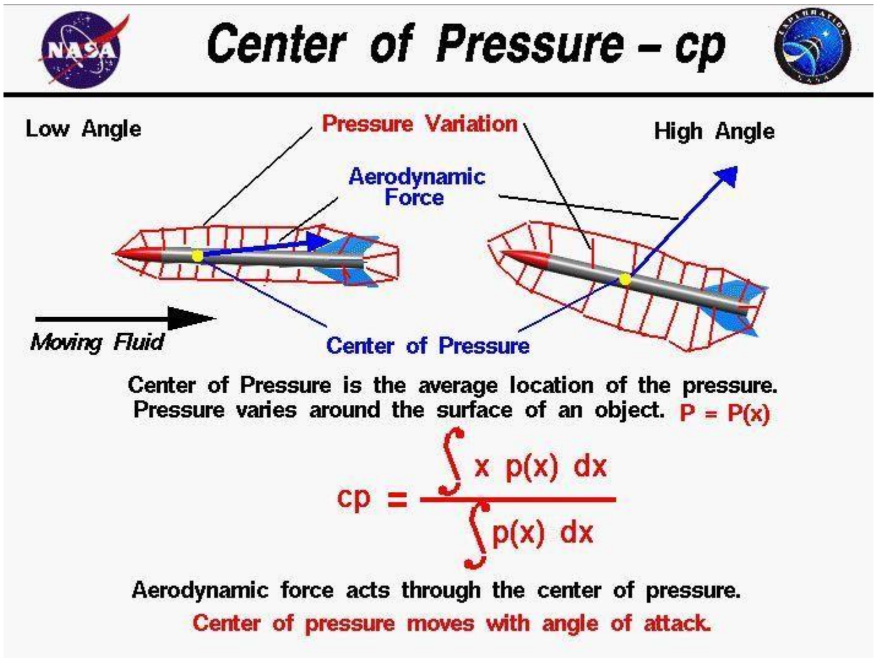
Airframe Design

As an intro to amateur rocket design, one must decide if the rocket will have a single diameter length, and if it will be going supersonic. This rocket only has two body tubes, fins, and a nose cone.

All of the modeling was done with SolidWorks 2013 on a Student Version. To start a design, the user must first understand what diameter body this rocket will have. Since this will dictate other dimensions for the nosecone and fins. One should take into consideration firstly what payload the rocket will hold. For this project the internal payloads were the 2 avionics systems. Since the avionics system was going to be built from hand, the space needed by Yuan wasn't initially clear. After some research on common body diameters and typical weights, a 4" diameter rocket body was chosen. We were lucky enough to have 4" cardboard tubing donated to us. As a rule of thumb the 1st stage fins are sized with twice the body diameter (D) for the span and root chord, and a single D length for the tip chord. The 2nd stage fins were sized with a 2*D root chord but the span needed to be shorter in order to have the 1st stage fins have undisturbed flow at the tip. A 2nd stage span of .625*D was used and a root chord of .8675*D. The body tube length for both stages was set at 30in, which was the cut length they were donated as. A few more inches would have been appreciated for both stages. The nose cone was a selected ogive shape. As a rule of thumb, the nosecone length is given by anything reasonable above 2*D. The ogive curve allows for the lease amount of drag as the end of the nose cone curves and ends parallel to the body. The nose cone length was 11".

Barrowman Equations

To stabilize any rocket a counter force must be applied to correct for any resultant force forward of the center of gravity, CG. This resultant force is due to the center of pressure, CP. Each component has a center of pressure, however the body's cylindrical shape causes that CP (for the body tube) to be negligible. One can think of the CP as if all the aerodynamic force on that body were summed up and applied to one location, equivalent to what it actually is. It is a location of a resultant force due to the pressure distribution over the area the component or body has.



Center of Pressure is the average location of the pressure. Pressure varies around the surface of an object. P = P(x)

$$cp = \frac{\int x\ p(x)\ dx}{\int p(x)\ dx}$$

Aerodynamic force acts through the center of pressure.

Center of pressure moves with angle of attack.

Figure 1: Center of Pressure from NASA.gov

For a single diameter rocket body, the nose cone and fins will dictate the location of the CP. To calculate the CP location there are a few reliable equation developed by James Barrowman, that will give decent theoretical results[1].

$$C_N = 2$$

Nose Cone Coefficient

$$X_N = .466L_N$$

Nose Cone CP location

$$C_F = \left[1 + \frac{R}{S+R}\right]\left[\frac{4N\left(\frac{S}{d}\right)^2}{1+\sqrt{1+\left(\frac{2L_F}{C_R+C_T}\right)^2}}\right]$$

Fin Term Coefficient

$$X_F = X_B + \frac{X_R}{3}\frac{(C_R+2C_T)}{(C_R+C_T)} + \frac{1}{6}\left[(C_R + C_T) - \left(\frac{C_R C_T}{C_R+C_T}\right)\right]$$

Fin CP location

$$\bar{X}_{Cp} = \frac{(C_N * X_N + C_F * X_F)}{C_N + C_F}$$

Total CP location

---

[1] The equations shown do not include Conical Shoulders or Conical Boat Tails

Nomenclature:

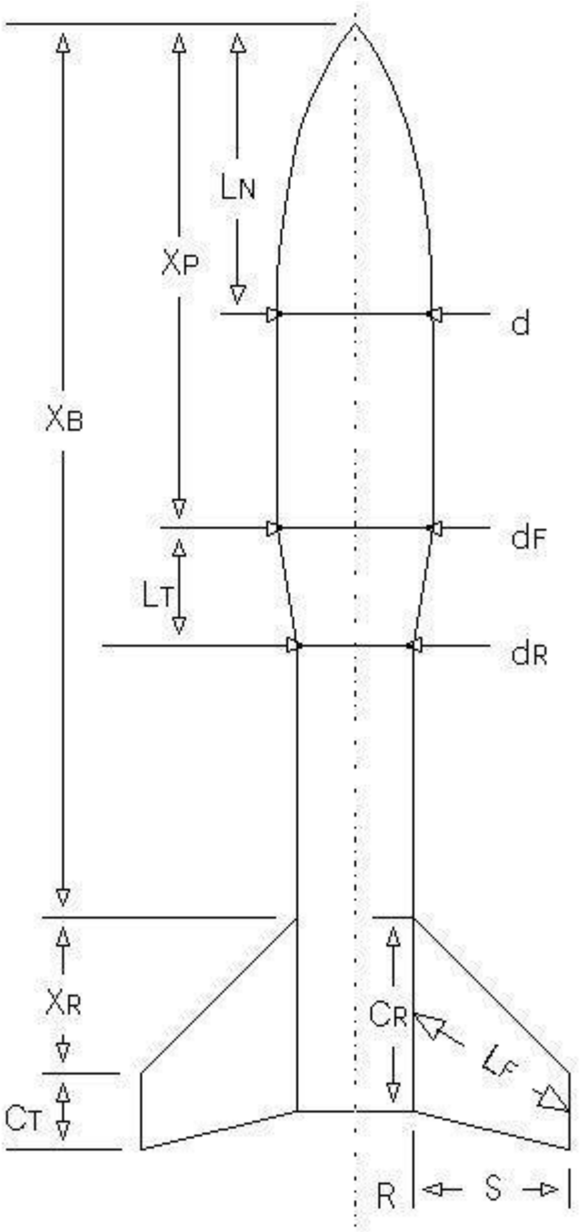


Figure 2: Barrowman Equation Nomenclature from Randy Culp at Tripoli

LN = length of nose

d = diameter at base of nose

dF = diameter at front of transition dR = diameter at rear of transition LT = length of transition

XP = distance from tip of nose to front of transition

CR = fin root chord

CT = fin tip chord

S = fin semispan

LF = length of fin mid-chord line

R = radius of body at aft end

XR = distance between fin root leading edge and fin tip leading edge parallel to body

XB = distance from nose tip to fin root chord leading edge

N = number of fins

The Length of the Fin mid-chord line here assumes that you have a fin ready to measure. To calculate this L_F term, use the following equations. Where θ is the sweep angle of the fin:

$$m = S * \tan\left(\theta * \frac{\pi}{180}\right); \qquad L_F = \sqrt{\left(\left(\left(\frac{C_T}{2}\right) + m\right) - \frac{C_R}{2}\right)^2 + S^2}$$

Center of Gravity

Measuring the center of gravity location is similar to measuring the location of the center of pressure. One needs the weight and CG each component, but calculating this early on will constrain the fabrication portion. The actual CG should not stray too far from the design CG.

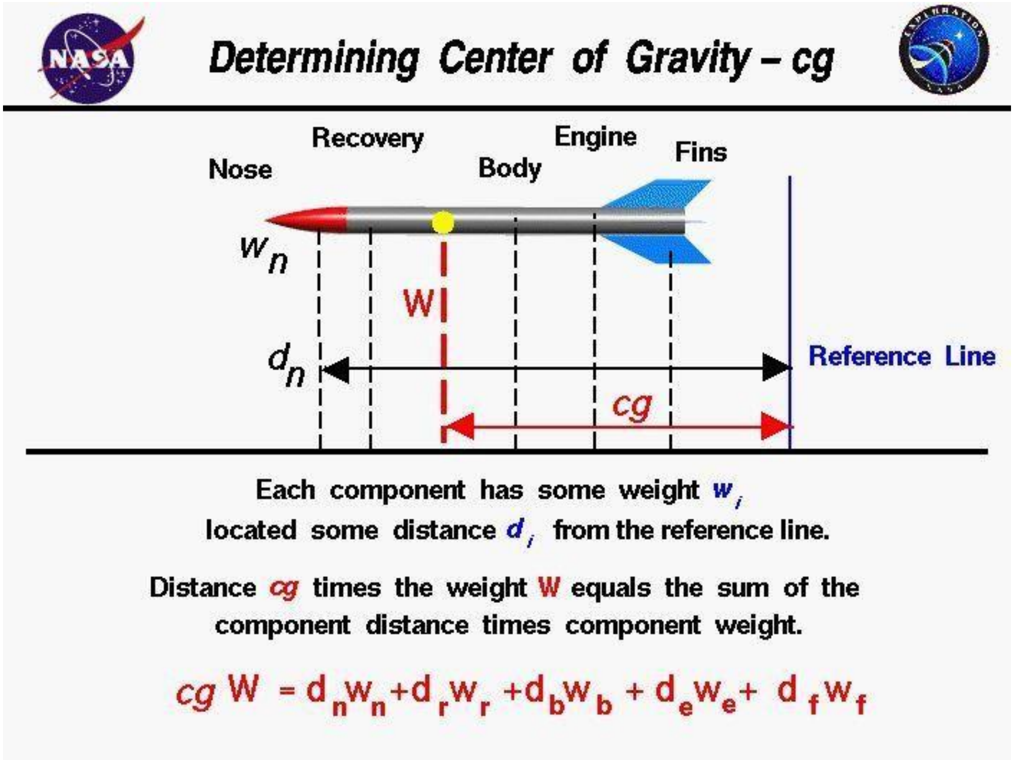
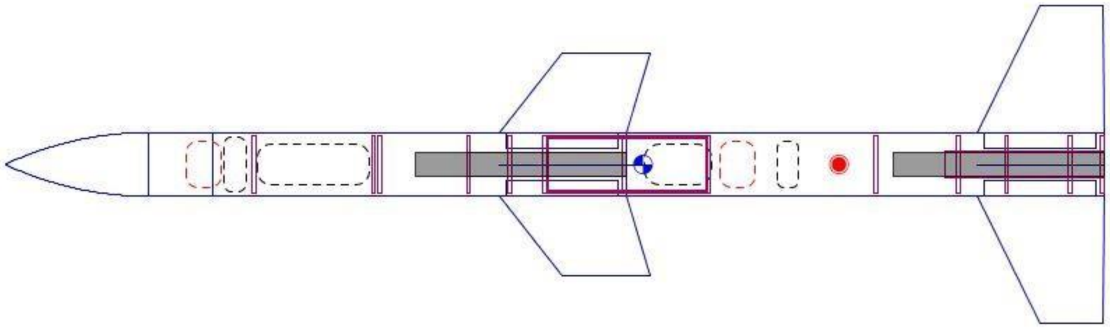


Figure 3: Center of Gravity Location from NASA.gov

Since much of the rocket was not readily available to actually weigh, the CG was estimated in the design program OpenRocket. As the parts of the rocket were fabricated the weights were recorded and overridden to update the model. CG (blue dot); CP (red dot).



Initial CG and CP Locations

CG = 44.42in from nose tip

CP = 54.83in from nose tip

2nd Stage CG and CP locations

CG = 26.73in from nose tip

CP = 32.86in from nose tip

Design

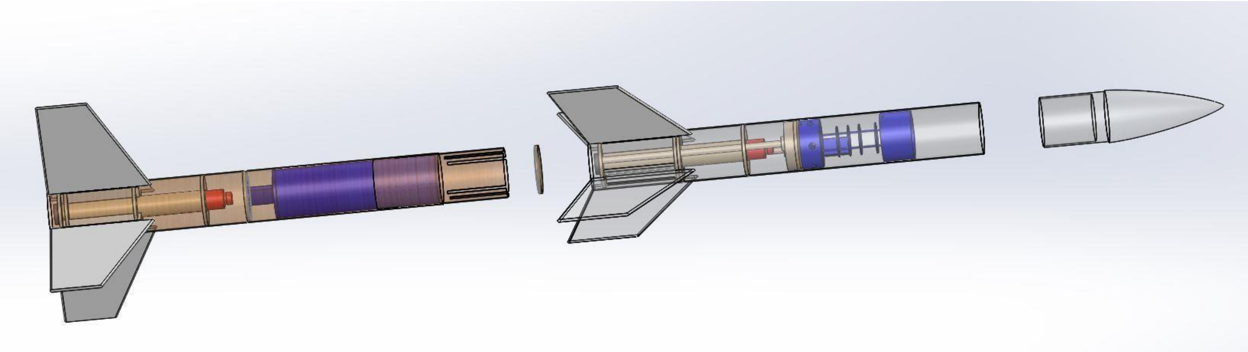


Figure 4: Final Design

The Rocket is comprised of two stages, a free bulkhead, and a nose cone. The first stage motor section forward closure is sectioned off to protect the avionics from any pressure spikes. The fins were slot body mounted for both stages. Both body sections were 30in with the nose cone at 11in. The parachute ejection charge for the first stage was controlled by the 1st stage avionics. The separation charge, 2nd stage motor ignition, and the 2nd stage parachute ejection charge were controlled by the 2nd stage avionics.

A simple slip fit was used for the coupler and was located on the first stage. The coupler had slots to accommodate the fin tabs of the 2nd stage, and allowed the 2nd stage thrust plate to fit inside of the first stage. The 2nd stage motor would push against the thrust plate which transfers the thrust to the fin tabs it rests on. This thrust transfer method was also used for the 1st stage.

The nose cone used a slip fit and was aided with two #4 nylon screws that acted as shear pins. Initially a camera was intended to be mounted at the nose cone, but they camera lens was damaged the day before the launch. We decided to use a different model camera simply taped to the body of the 2nd stage with a foam fairing to aid with drag reduction.

Pressure ports were used for the two forward motor closures, and one for each pressure sensor. A single hole is desired as to avoid an air flow across the pressure sensor. The barometric sensor should act as a static pressure sensor. Multiple pressure ports (openings to atmospheric pressure) will allow for false readings in static pressure.

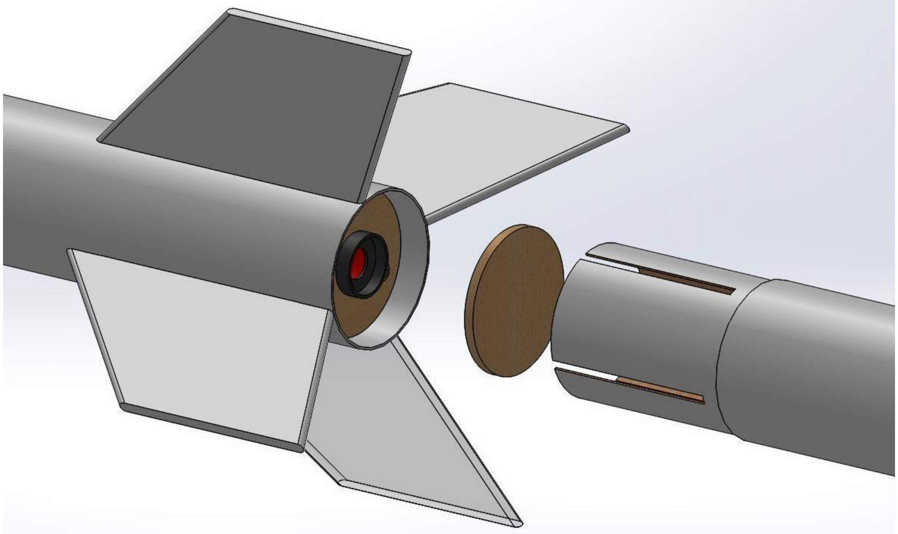


Figure 5: Coupler Section

Fabrication

The discussion of fabrication will be explained quickly with emphasis on what tools were necessary.

Airframe:

The cardboard tubes were wrapped in 3 layers of fiberglass and epoxy for strength.

Figure 6: Vacuum Bagging a Cardboard Tube

The fins were cut, sanded, and wrapped in 1 layer of fiberglass and epoxy. Bulkheads were cut using a router and cut to various sizes from the same ¼” plywood the fins were cut from. The Coupler was made from an extra cardboard tube that was cut into thirds and made to fit inside of the tubes. The coupler was fiberglassed and epoxied as well with a single layer, then epoxied to one of the body tubes.

The nose cone was extremely difficult to fabricate. As an ogive nosecone is made from a mathematical curve. The curve was made in solidworks, then printed on paper and used to cut out a stencil on wood. That stencil was then used to make a base for a wood lathe built from scratch. With a dremel bit lined up with the rotating shaft and the edge of the stencil, the dremel would carve everything that is not within the stencil’s line, leaving a prefect nose cone shape.

Figure 7: Wood Lathe for Nose Cone

Figure 8: Completed Nose Fairing

For future reference, if one were to try to recreate this process, use a single block of foam. The method here used three glued blocks of foam, however the areas where the glue was made the final product to be a little bumpy. One might be better off purchasing a premade nose cone. For the Shoulder of the nose cone, a part of cardboard tubing was used and glued under the nose cone.

Pre-Launch Procedures

The trip to the Friends of Amateur Rocketry (FAR) Site was indeed far. On a clear and cold day we were ready to set up everything and launch. The prefight procedure consisted of: Vehicle Inventory, Avionics Test, Engine Setup, Electric Matches Setup, All Electronic Connections, Recovery Setup, Final Set Screws for Both Avionics, Motor Insertion, and Stage Connection.

Vehicle Inventory:

The following list dictates the parts that are used to put together the 2stage rocket. They are bulk parts that might consist of separate parts themselves.

Bulk Parts List for this 2 Stage Rocket:

- Nose Cone
- Two 4 foot Parachutes
- Two 15 foot nylon webbing shock chords
- 2 quick links
- Steel Wool
- Protective Sheets
- Two Avionics Systems
- Wood Disk
- 1st stage body
- 2nd stage body
- eight #4 1-inch Set Screws
- 5 Electric Matches
- 2 J-size 38/720 Propellant Casings
- 2 Propellant Packages
- 5 grams of ffffg Black Powder with aluminum foil tape
- 2 Thrust Plates
- 2 Engine Retainers
- 4 Retainer Screws
- Camera
- #4 Nylon Screws

Avionics Test:

The avionics test consisted of turning on the two avionics and waiting for an acoustic sound telling us that the system was powered properly and ready to be used.

Engine Setup:

The two J350W motor reloads from Aerotech are packaged in a single bag but are not constructed for use. Clearly for safety reasons, the engine should be disassembled upon arrival. Each Propellant grain is also packaged in a separate bag for extra safety. The package consists of Forward and Aft O-rings and closure disks, along with the set up for the delay charge. It also comes with a full set of instructions for assembly. Once the engines were prepared and inside the casings they were set aside.

Electric Matches Setup:

Electric matches are explosive components that detonate when a specific current is reached in the circuit. They are used to ignite the motors, detonate separation charges, and eject parachutes. We initially calculated the suggested amount of black powder using an online calculator from Info-Central. However after the tests it was advised that we exceed the calculated amount as a “for sure” approach for separation and ejections. We ended up using 2 grams of black powder for the parachutes and 1 gram to aid in separation. The ejection charge calls for a small plastic bag, an E-match, aluminum foil tape, and your black powder.

Steps to create an ejection charge:

1.) Measure your black powder and pour into small zip-lock bag, hold it so the powder is packed into one corner.

2.) Put the firing end of the E-match deep within the pocket of black powder and seal the bag.

3.) Fold the Bag in a manner that keeps the powder compact and the E-match seated.

4.) Use Aluminum foil Tape to completely seal the folded bag.

(a) Burn rate for black powder increases as a function of pressure, so it is wise to wrap the bag in tape very tightly.

(b) Make sure there are no open ends to the tape seal.

Electrical Connections:

Three of the charges are wired to the 2nd stage avionics and the fourth charge is connected to the 1st stage avionics. There is a male header clip located on the 2nd stage avionics that clips to a wire extension that runs along the length of the 2nd Stage Body. That clip feeds the wired ends to the 2nd stage engine ignitor, separation charge, and the infrared separation detection sensor. On top of the 2nd stage avionics is a header clamp used to connect the parachute ejection charge, same for the 1st stage avionics.

Parachute Setup:

One end of the shock chord is tied to the apex of the parachute the other end of the chord is tied to the quick link. The parachute shroud lines are grabbed by the apex and placed inside of the parachute canopy to ensure the least chance of entanglement. The remaining shock chord is taken and folded in a serpentine manner. For every 6 or 7 folds, that section is held together by masking tape. The masking tape provided extra resistance to the overall force felt by the rocket body at the parachute inflates. The tape must break away. Starting from the quick link up to 1 foot, the shock chord is covered in aluminum tape to protect it from the ejection charge. The parachute canopy is folded into a tight roll. The Shock Chord and canopy are wrapped in the protective shroud. Steel Wool is used in between the ejection charge and the parachute to suppress the flame from the explosion.

Set Screws:

It was advised that we should use four #4 machine screws to hold in the avionics to the airframe as it descends with the parachutes. The screw alignment were aligned to the fin arrangement to decrease drag, however this decreases fin effectiveness as air becomes disturbed upstream prior to meeting the fins. With the Avionics in place they are screwed in. Keep in mind that the screws aren’t meant to completely be screwed in for this design, they are just meant to hold the airframe to the avionics by subjecting the screws to shear. The screws never experienced tension.

Motor Insertion:

With the motors prepped, we first placed the thrust rings into position then we slipped to separation match through the 2nd stage thrust ring wire hole. The motors where then placed in their spots and held in with the motor retainers. The Engine Ignitors are then inserted.

Stage Connections:

At this point it became a matter of slipping the 1st stage coupler into the second stage.

Problems before Launch

To launch an amateur rocket you need either a lunch lug or rail buttons. This design implemented rail buttons for their small size and ease to incorporate. ¼" Rail Buttons were used. Ideally you would put one rail button at the base of the entire rocket and the second button at the Initial CG. Since the center of gravity was not calculated fully due to the unknown exact weight of the engines it was calculated the night before and the second rail button was mounted to the airframe. The location of the 2nd rail button was located 2 inches above the calculated CG. It was necessary since the screw that protrudes to hold the rail button would have been a problem if it was on the first stage where the CG resided. This meant that the sleeve on the 1st stage needed a slot to be cut for the rail button screw to pass through.

There was an unforeseen spacing problem with the 2nd stage engine. When one assembles an engine reload, a red ignition/pressure cap is placed over the nozzle. This protruded too much for the first stage pressure cap to fit (the wood disk meant to protect the parachute from the separation charge). The parachute cavity had to be cut away some to make the two stage fit together.

Using a Dremel solved both of these problems.

Figure 9: 2 Stage Structure

The Launch

Figure 10: Just before Launch

After a 5 second countdown, the 1st stage engine ignited and propelled the rocket upward straight with a slight tilt about 60ft up. Just after burnout the first stage parachute was ejected and immediately ripped off from the shock chord. The 2nd stage soared upwards straight to a 446m (1463ft) apogee. The 1st stage plummeted straight into the ground destroying the 1st stage avionics and half to the 1st stage airframe. Thankfully the 2nd stage was recovered safely, the 1st stage parachute was recovered undamaged, and the fin box for the 1st stage is easily salvageable. It was noted that the 2nd stage engine did not ignite.   Strangely the **separation charge did not detonate**.

Failure Analysis Part 1

The following figures are listed by single numbers and will be considered as a group for the failure analysis. The following analysis is a majority of the firsthand account of Brandon Hernaez.

From what I saw after reviewing the onboard video, the parachute was pushed out by the ejection charge early causing it to be ripped off due to the high speed the 1st stage was traveling. The 1st stage body came down hard and flat, truncating the top half of the body, completely destroying it (photo 1). Upon further inspection Yuan and I decided that the pressure sensor did not malfunction since we had effectively tested it in a vacuum chamber. It had to have felt a pressure increase to think it was falling and released the parachute correctly. The pressure port for the pressure sensor is located about 9cm from the pressure sensor and is fairly oversized. The bulkhead below the 1st stage avionics is completely sealed and airtight from my own tests. Photo 3 depicts the bulkhead above the engine and photo 6 is the exhaust port for the delay charge above the motor. With black soot coming from the port, it is clear that that cavity experienced some pressure increase. Upon removing the bulkhead, I looked inside that cavity. The entire space was covered in soot. My understanding is that the delay charge is supposed to last for a 14 seconds and release a light puff of gas. Photo 8 is the underside of the bulkhead completely covered in soot but does not look charred.

It is fair to mention that we used a completely new type of reload set up for this stage. AeroTech gave us a reload where the forward enclosure section was completely assembled, therefore I did not pay any more attention to it.

This is what I think happened: Near burnout, the delay grain failed or burned too quickly causing high a very high pressure spike to occur cracking the bulkhead. With that crack, the pressure sensor detected an increase in pressure and ejected the parachute. The parachute was not tied tight enough to the shock chord and failed to stay attached, photo 2, 1, and 4 show the quick link and shock chord still in one piece. It is hard to tell if this is the case since the forward motor casing fractured the bulkhead upon impact, so small fractures cannot be distinguished. In photo 9, the forward enclosure was looked at carefully by Dave McCue and it was noted that grease was not placed in the powder cavity to stop hot gasses from escaping.

The 2nd stage mishaps with the ejection charge not going off will be explained by Yuan Zhang in part 2 of this report.

2nd Chance Part 1

A few things we have decided to do next time. We will not rely on pressure sensors for the 1st stage; instead, we will use an accelerometer to simply detect an apogee since we only want to recover this stage safely. Secondly we have decided to use a larger bulkhead for the 1st stage motor cavity to ensure no possible overpressureization.

1

2

3

4

5

6

7

8

9

Results and Estimations

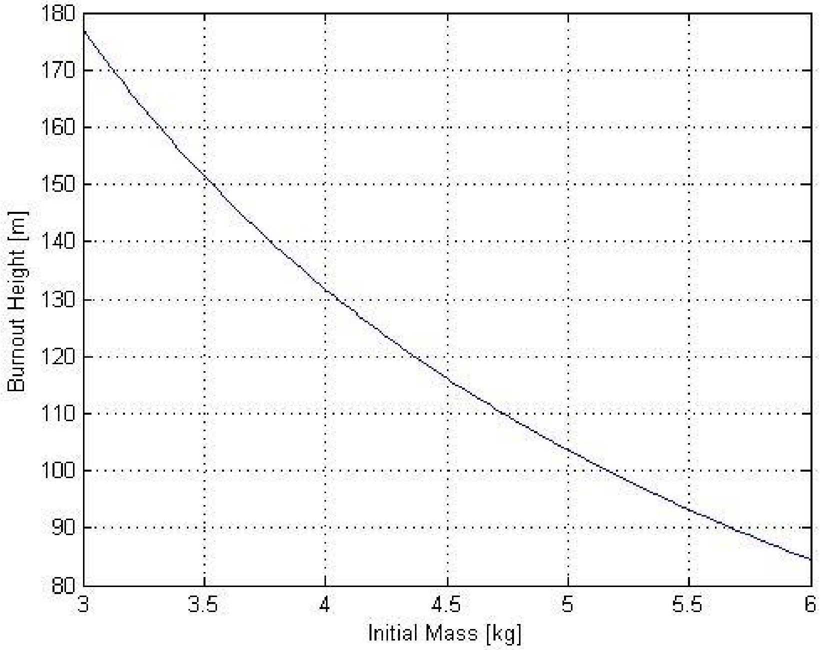


Figure 11: 1st Stage Engine Burnout Height

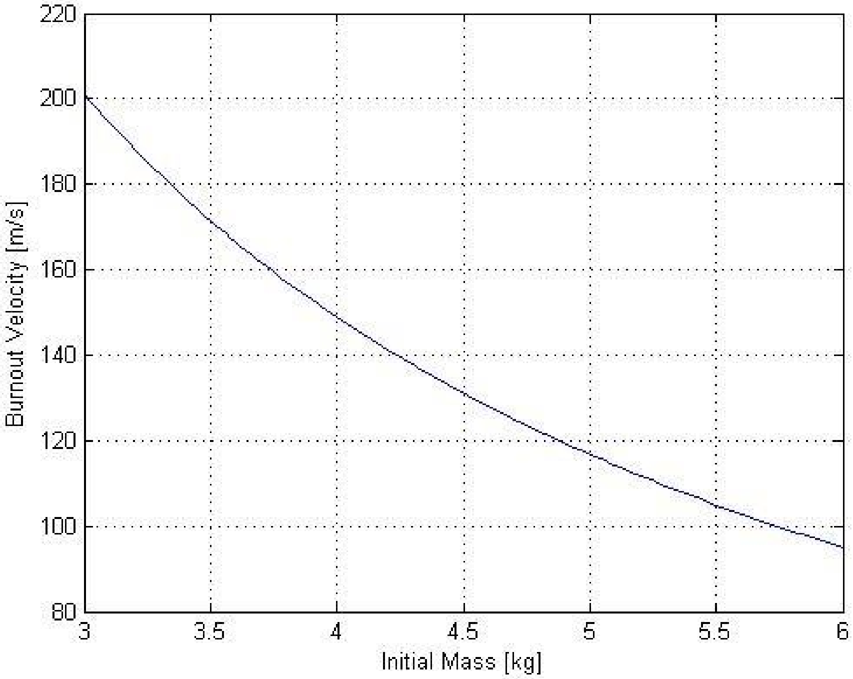


Figure 12: 1st Stage Burnout Velocity

This launch was main concerned with the separation of the two bodies. We mainly looked at when the separation would take place; and by using MatLab, the theoretical burnout heights and velocities were calculated with respect to the initial mass. The reason why burnout is such an important phase is because it is the fastest the 2nd stage will coast after separation. By the time the bodies separate, the effective drag on the 2nd stage body will have dropped significantly and will thus slow down at a slower rate. It is also crucial that the 2nd stage be ignited just after separation since the fins are most effective with the highest possible velocity in this situation. Further, since the bodies separated the 2nd stage has to spend time determining the orientation and igniting the engine. If the vehicle is too slow, even with a good orientation, by the time the engine ignites the effective velocity might be too slow and the sudden thrust could cause it to drastically change direction. With that in mind, it wasn’t necessary to calculate maximum height for the second stage. It simply needed to ignite the engine or eject the parachute. The failsafe system worked by checking if the rocket has at least reached the 1st stage burnout height.

The x-axis for the two plots above where necessary since the rocket wasn’t finished until the very last week. Final weights weren’t conclusive until launch. The final weight during launch was a little over 5.4kg. The Estimated height was calculated with three different tools. Open Rocket, MatLab, and by hand. Open Rocket estimated a burnout height of 136m (including drag), Matlab calculated near 94m (no drag, constant gravity), my own hand calculations resulted in 100m (estimated drag, constant gravity). Surprisingly the altimeter onboard recorded a separation altitude of 123m.

Part 2 (Prepared by Yuan Zhang)

Final Fail-Safe System Design

The fail-safe system was developed in the Arduino platform because the Arduino platform has a lot of open source libraries, which can simplify our work. In order to minimize the size of the system and ensure the reliability of the system, I used four Arduino Pro Mini. The Arduino Pro Mini is the minimum size of an Arduino that is available in the market. The system consists of four subsystems, in which three of them work independently.

(1) Recovery Subsystem

This subsystem is used for the recovery of the rocket. It consisted of an Arduino Pro Mini, a GPS, an Xbee Pro S1, and a Micro SD module. The GPS was used to acquire the current latitude, longitude, speed, and altitude of the rocket. The Xbee Pro S1 is a telemetry device. It can transmit data at maximum of 250kbps baud rate up to 1 mile (1500m) range. We have another Xbee Pro S1 connected to computer to receive and show the data. Its order was to receive all data. The transmission baud rate was set at 5600, and the receiver baud rate was set at 115200. The Micro SD module was used to store data. This subsystem work independently. It does not have communication with other subsystem. They only share the same power source.

(2) Altitude Record Subsystem

This subsystem consists of a BMP085 barometric sensor, an Arduino Pro Mini, and a Micro SD module. I originally planned to use the main system to store the altitude, temperature, and pressure data, but the recording procedure reduced the system update rate to 17HZ from 100HZ. The main system must have a high update rate to make reliable decision. Therefore, I add another subsystem to record data only. This subsystem also works independently. It only shares the power source with others.

(3) Attitude Module.

This subsystem consists of a Serial MPU6050 (IMU), a Micro SD module and an Arduino Pro mini. The Serial MPU6050 is based on MPU6050, but it has a built in processor that can output the Yaw, Pitch, and Roll that have passed Kalman Filter through serial communication. The serial receive procedure interferes with other procedure in the main system, so I have to make a subsystem for IMU. This subsystem receives the serial data form IMU and store data in Micro SD module. It processes the Yaw Pitch and Roll and determines whether the attitude is safe and then output the results to main module through making digital pin HIGH or LOW. The system check results also send to the main module by using the same method.

(4) Main Module

This is the most important subsystem. It consists of a BMP085 barometric sensor, an infrared line follower sensor, a buzzer, three IRFZ44N Mosfect, and an Arduino Pro Mini. Infrared line follower sensor serves as separation sensor. It has a property that when it detects white color it outputs LOW, and when it senses black color or infinite distance, it outputs HIGH. We painted the connection part in first stage to white, and we mounted the sensor in second stage. When the separation is complete, sensor cannot sense white anymore and then we know the separation has completed. The barometric sensor is used to get altitude. All decisions is based on altitude such as the separation start and apogee detection. The buzzer provides feedback to us. When the system check starts, there will be three short beep, and when the system is ready, there will be a long beep. If the system is not ready, the alert will be turned on. If the rocket has passed the apogee the alert will also be turned on. In addition, the Mosfect serves as switch. When it will be turned on as the current passes through the electric match and the electric match is ignited. Relay can serve as the same function but the mechanical design inside the relay causes it to be unreliable in high acceleration application. Mosfect does not include any mechanical component. It uses a semiconductor instead. The size of Mosfect is smaller than relay, and it is more reliable than relay in high acceleration application.

(5) Power

There are two power sources in the system: Main Power and Ignition Power.
When the current runs through the electric match, it draws around 1A from the whole system. This is relatively high current in the system. If I only use one power source, during separation, ignition, or ejection, the Arduino might restart due to the low current supply. In order to avoid this from happening, I use another 1.5V battery as ignition power in addition to the 9V main power.

(6) Switch

There are a total of 6 switches in the system. Three front switches (big one) are used during the actual launch. Front Switch 3 will be turned on first. It supplies power to the Recovery module. The GPS generally takes around 2 minutes to get a fix, so the recovery module should be turned on before other subsystems. Front Switch 2 will be turned on right before the ignition. It controls the power supply to all subsystems except recovery subsystem. After the long beep (sign of system is ready), the Front Switch 1 will be turned on. It controls the ignition power. It is the last insurance in the system to avoid harming user. Three back switches are used for testing only. Back Switch 1 disconnects the serial communication between IMU and Arduino, and thus the new program is able to upload to Arduino. Back Switch 2 is used to switch power supply of attitude from main source to main module. Back Switch 3 is used to close the altitude record subsystem.

(7) First Stage Avionics

First Stage Avionics only has a BMP085, a buzzer, a mosfect, and an Arduino Pro Mini. BMP085 is used to get altitude and then using altitude to find apogee. Buzzer is used for recovery and feedback. Mosfect is used to eject parachute.

Abandoned Design

In the original design, first stage system has wireless communication with the second stage system. Separation is executed by first stage avionics. Orientation check and ignition are executed by the second stage avionics. I believed this can simplify the separation mechanism design. After consulting with Brandon and our advisor David, we decided to let the second stage avionics take care of everything because David was worried about the reliability of the wireless communication and Brandon had designed a separation mechanism that could be executed by send stage avionics. Another change is the separation sensor. In my original design, I used infrared line follower to sense the completion of separation and Hall Effect sensor to sense the start of separation. We used two sensors to ensure the separation is complete. However, after we finish the fabrication, we found out that there was no room for us to mount a magnet that is necessary for the Hall sensor. After consulting with David, we believed infrared line follower sensor should be adequate. Thus, I removed the hall sensor from the design.

Schematic

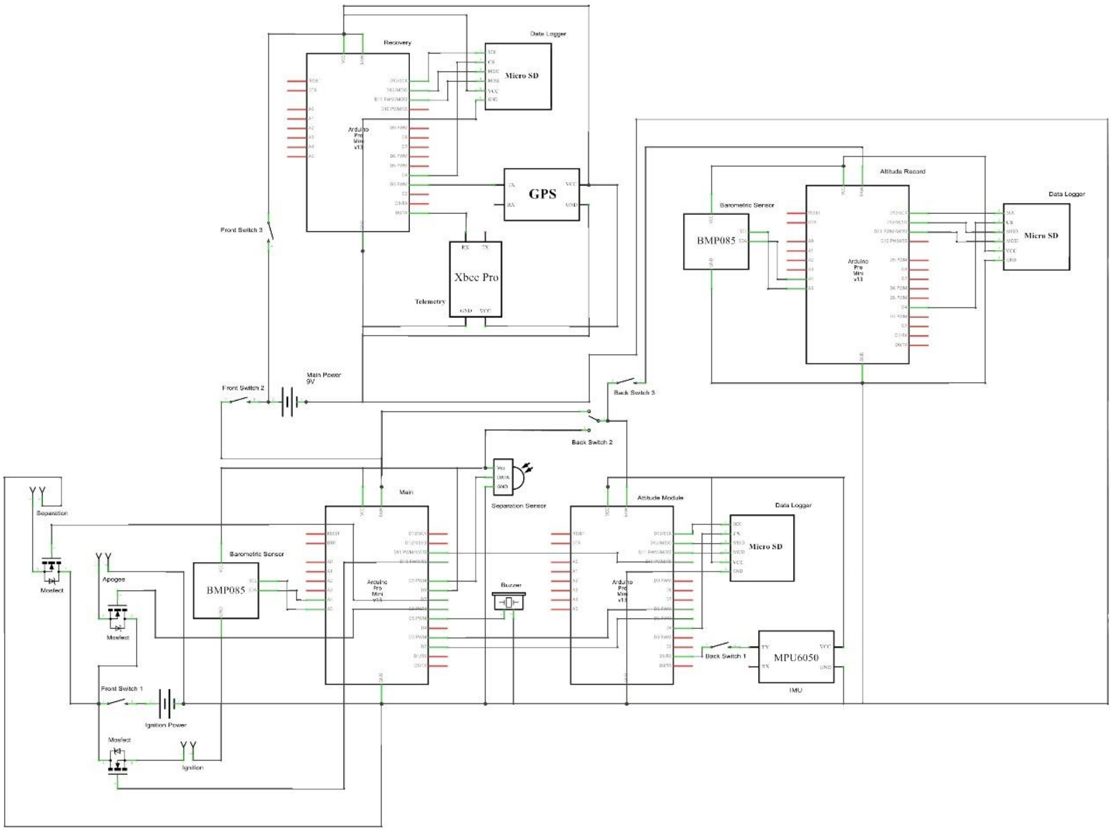


Figure1. Second Stage Fail-Safe System

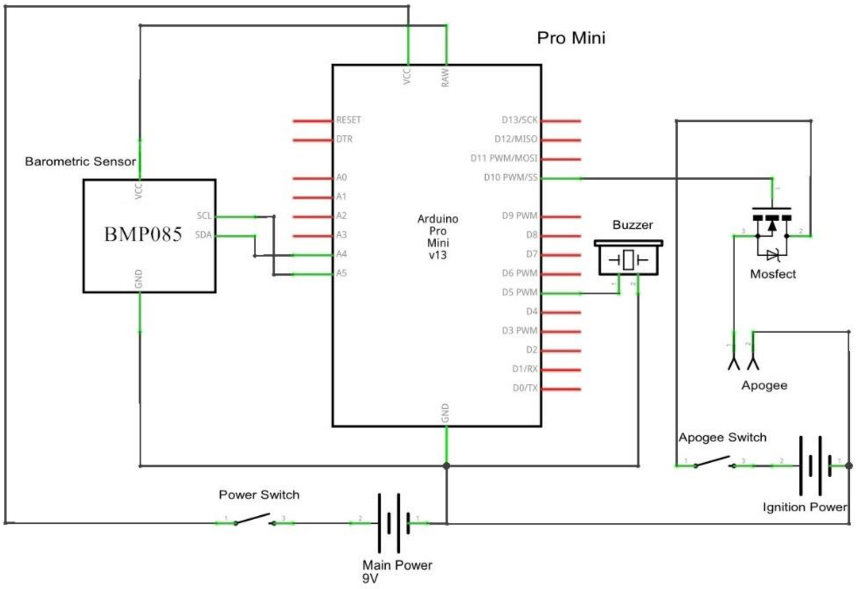


Figure 2. First Stage Avionics

Avionics Fabrication

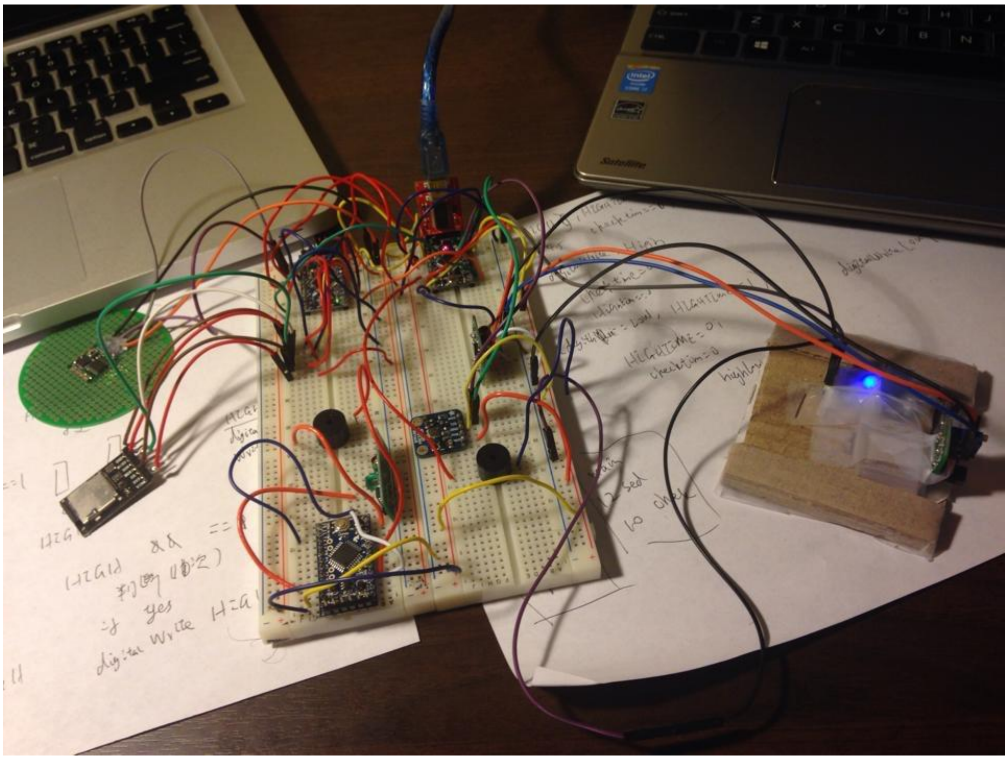


Figure 3. Prototyping

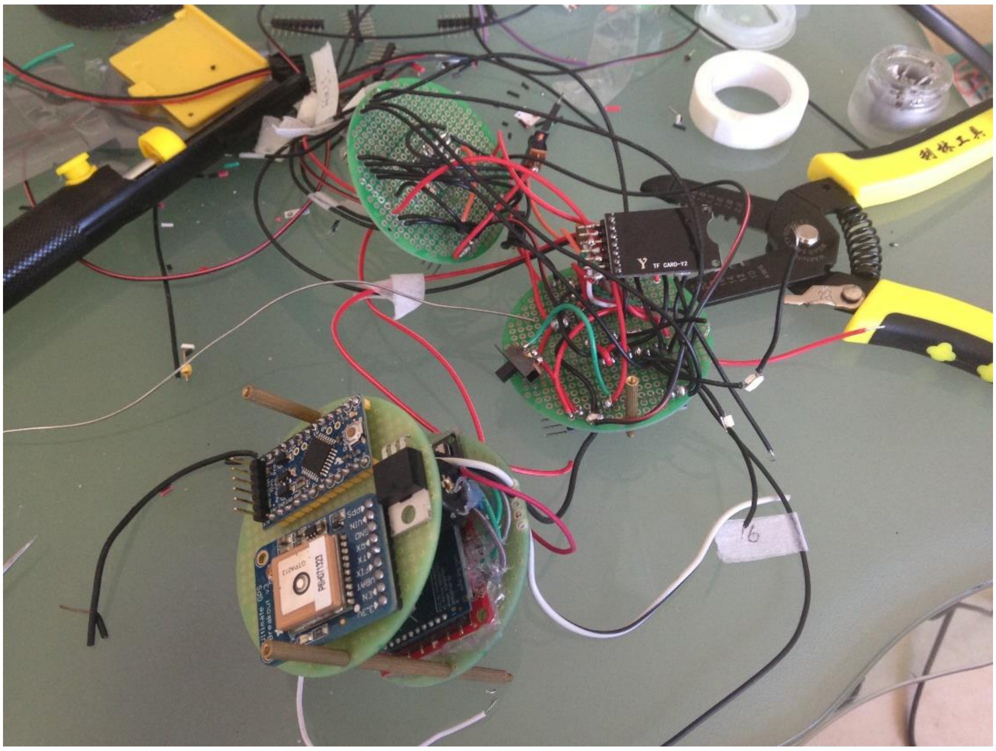


Figure 4. Soldering System

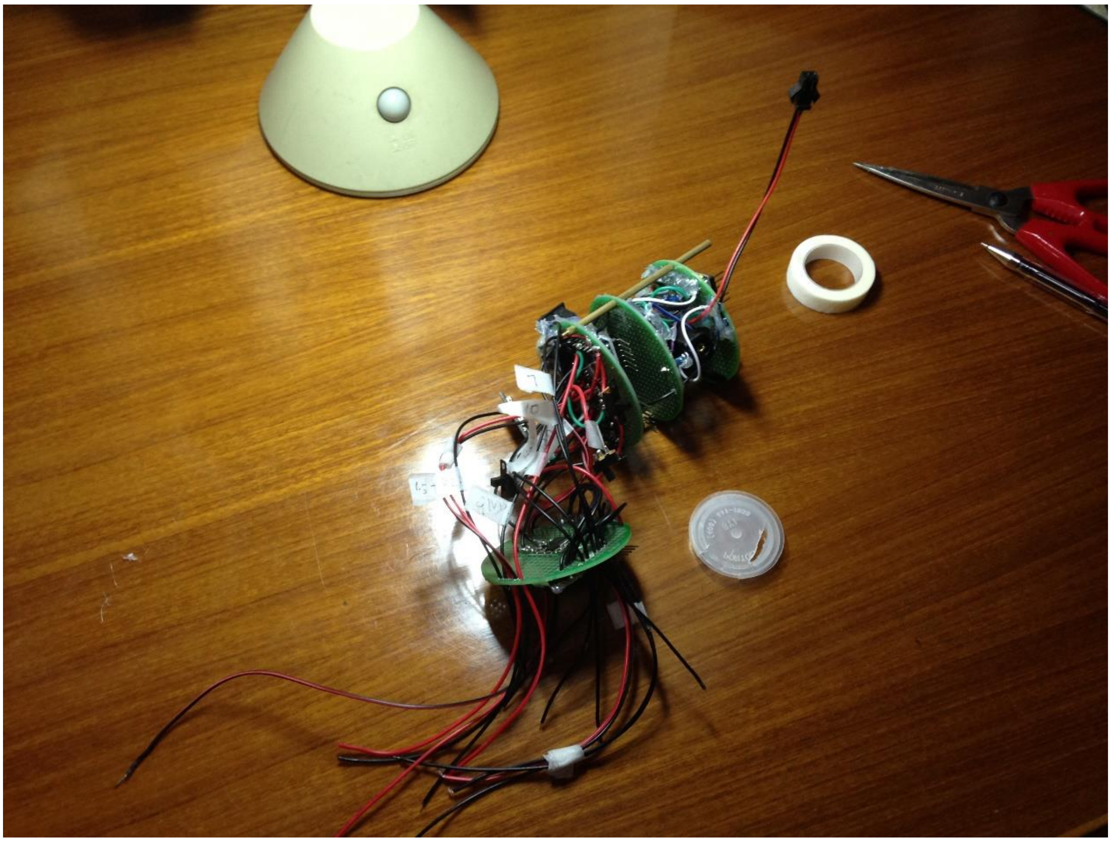
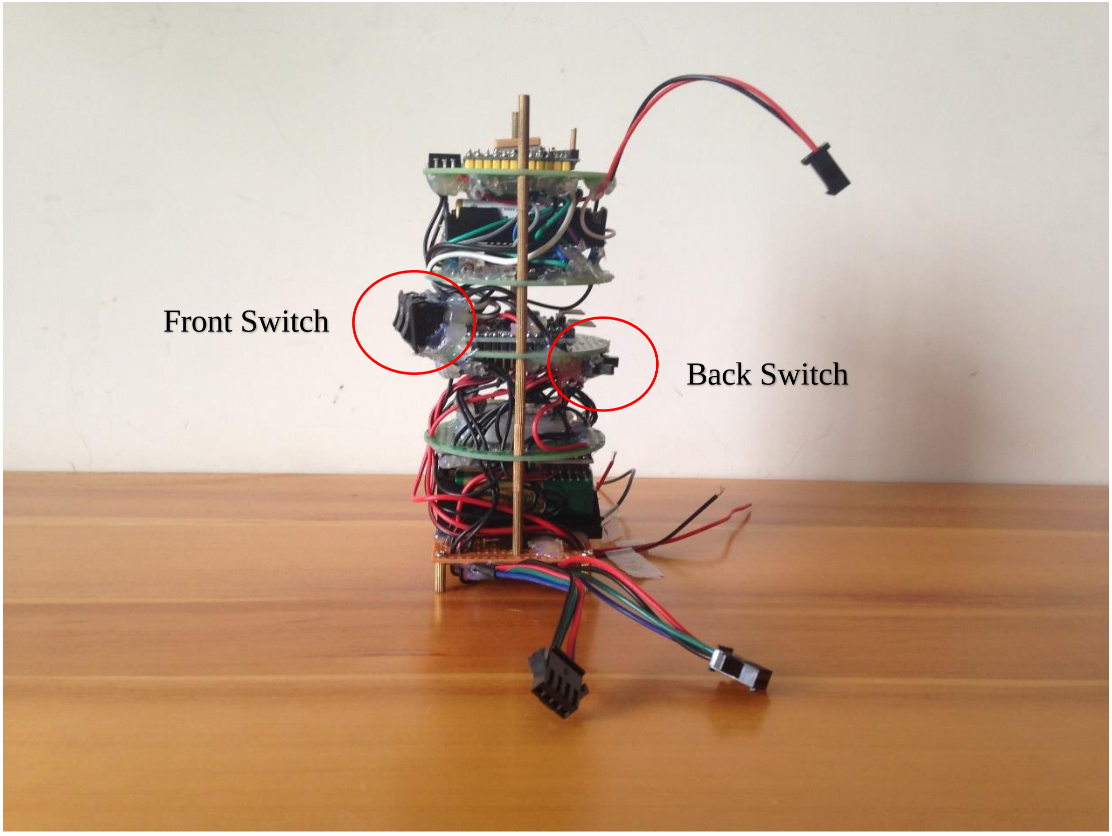


Figure 5. Completion of Main and Recovery Subsystem



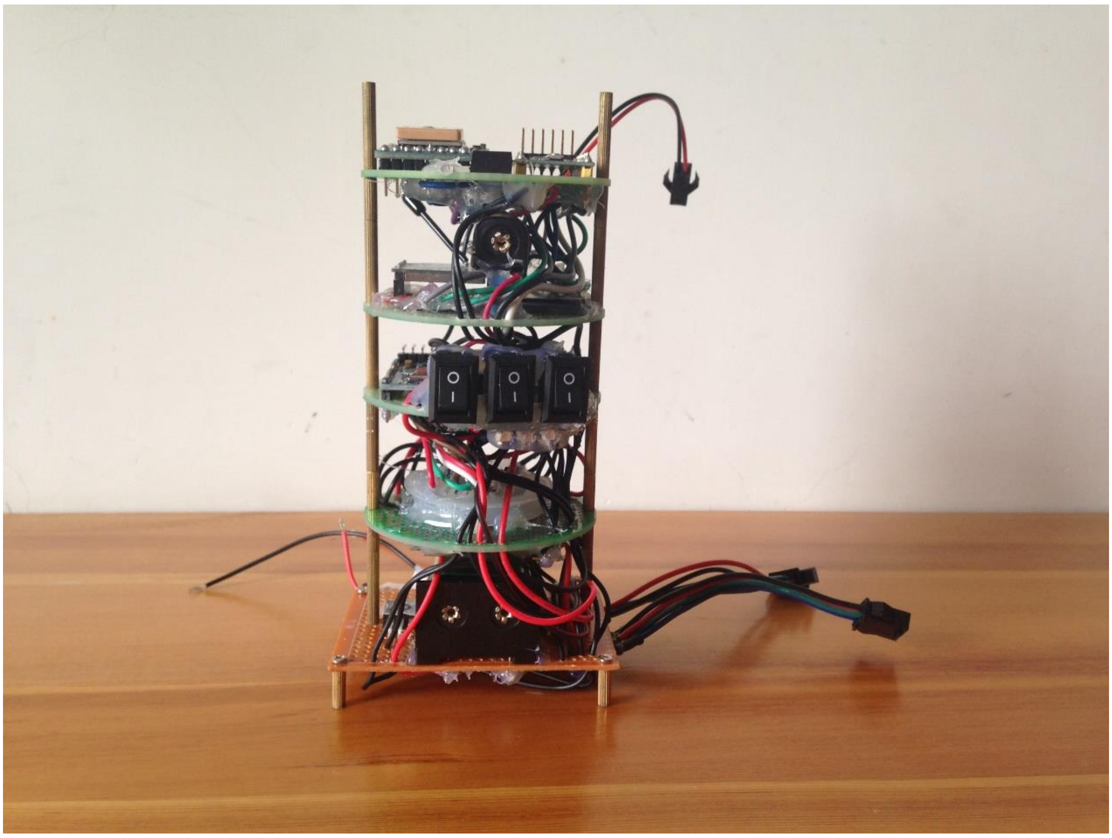


Figure 6 & 7. Completion of Fail-Safe System

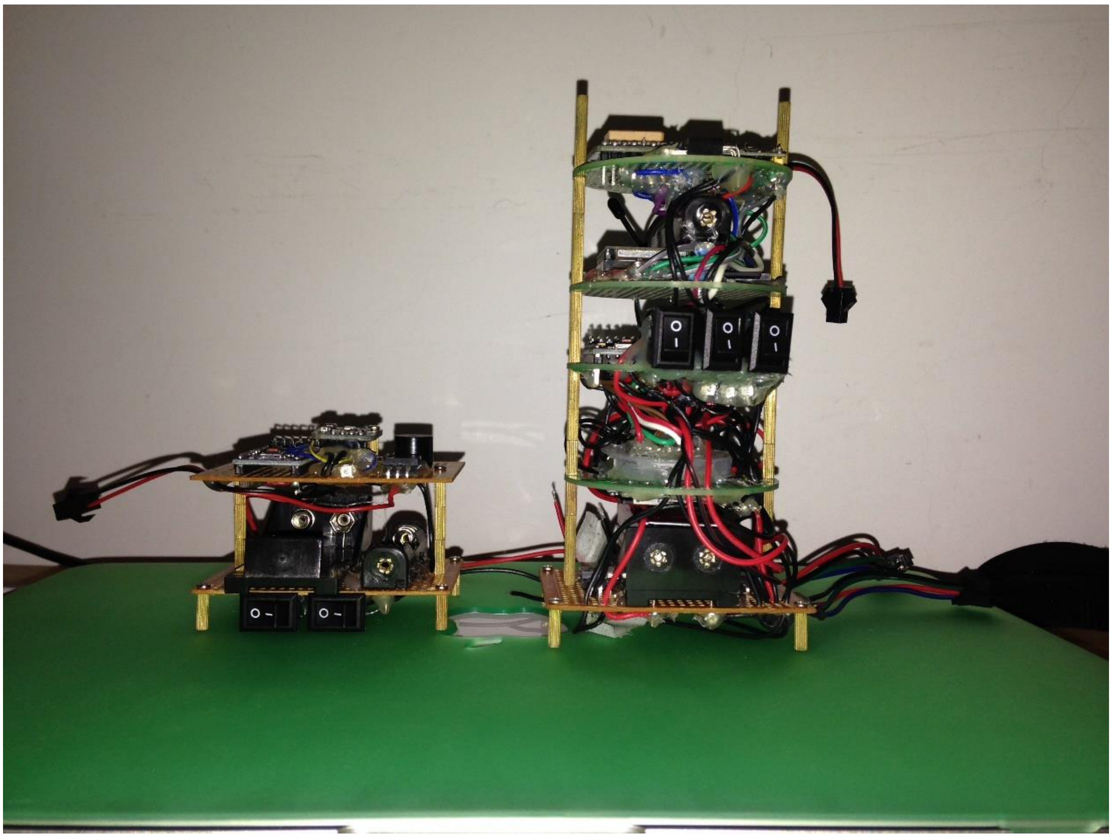


Figure 8. First Stage and Second Stage Avionics

Figure 9. Fail-Safe System inside rocket

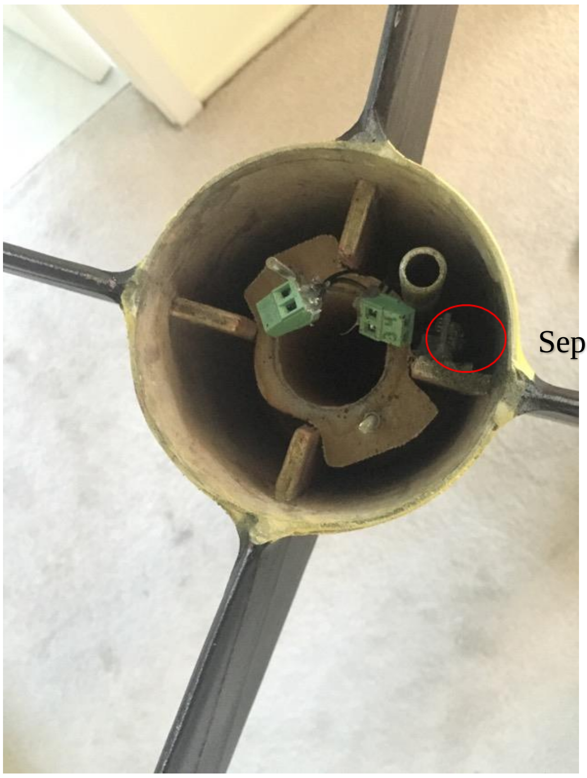

Separation Sensor

Figure 10. Connection Terminals for Separation and Ignition Charge, and Separation Sensor.

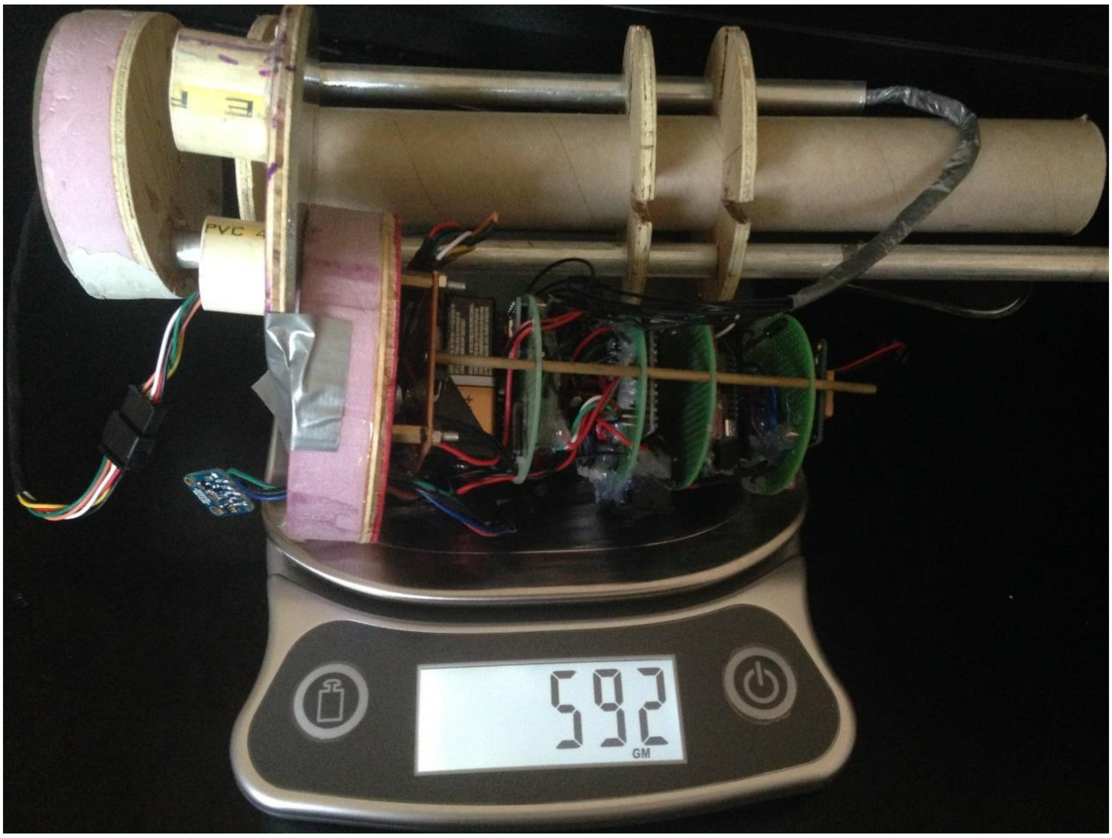


Figure 11. Weight of Fail-Safe System and Internal Structure

Fail-Safe System Logic

The goal of the fail-safe system is to deal with as many emergency situations as possible. This system can deal with five emergency cases.

Emergency Case 0

Case: System Failure. Some components in the system do not work properly.
Solution: Alert is turned on and program stop.

Emergency Case 1

Case: Liftoff is successful, but engine failure occurs.
Possible Result: Rocket cannot reach separation altitude
Solution: Second stage will not be ignited. Rocket separates immediately, both stages find apogee and then eject parachute.

Emergency Case 2

Case: Separation occurs before reaching separation altitude (Eg. 1st stage accidently ejects parachute) or separation sensor wiring is broke after liftoff
Solution: Second stage will not be ignited. Rocket separates immediately, both stages find apogee and then eject parachute.

Emergency Case 3

Case: Separation Failure
Solution: Second stage will not be ignited. Both stages find apogee and the eject parachute.

Emergency Case 4

Case: Second stage orientation is dangerous
Solution: Second stage will not be ignited. Both stages find apogee and the eject parachute.

For the first stage avionics, it only runs the system check.

The detail logic is referred to in the following section.

Flow Chart

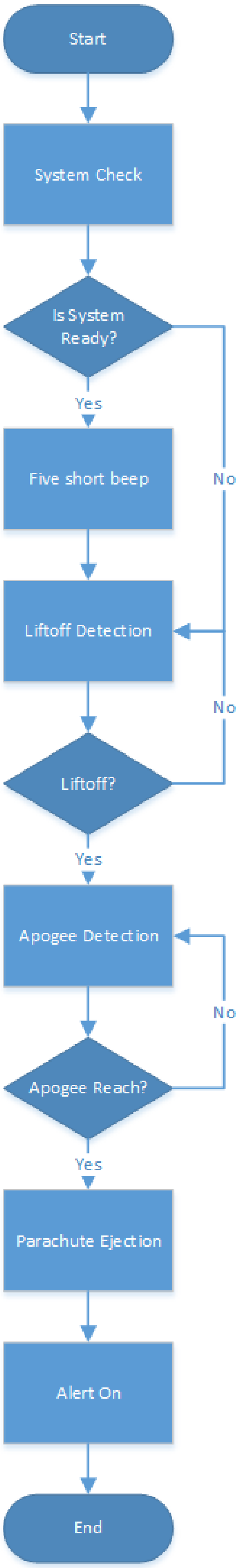


Figure 12. First Stage Flow Chart

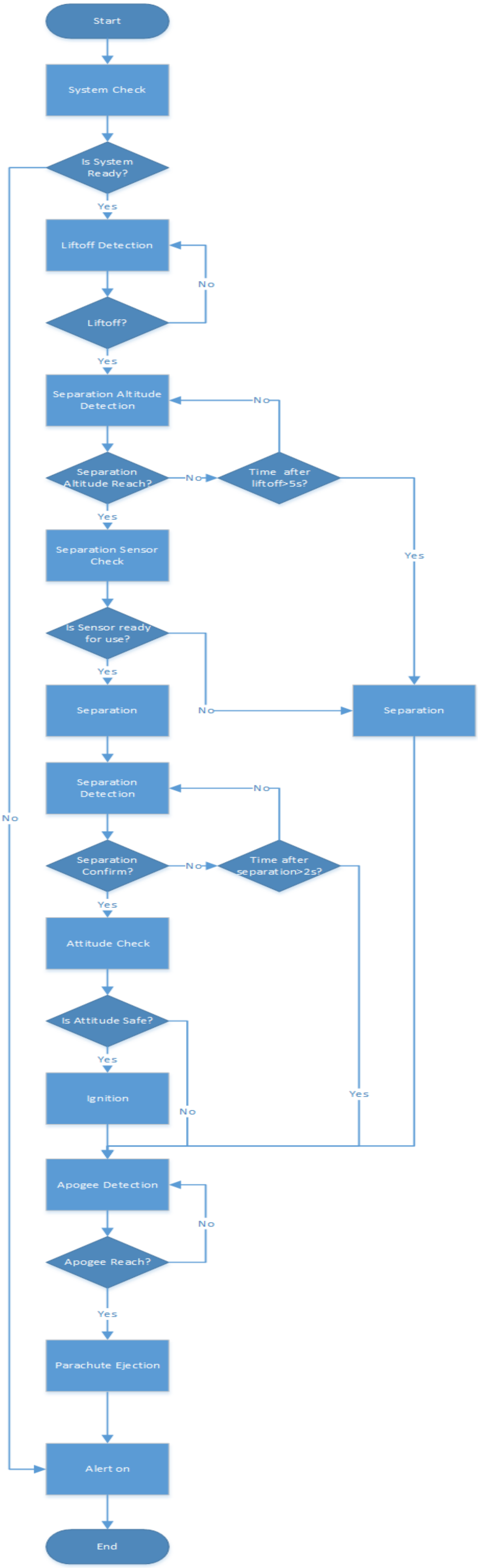


Figure 13. Second Stage Flow Chart

Pre-Launch Test

We conducted the separation test and parachute ejection test before the launch. David was concern about the separation sensor. He doubted that the smoke generated during the separation might cause the infrared line follower sensor failure. We conducted the experiment and proved he was wrong. All systems worked properly during the test.

Separation Test

https://www.youtube.com/watch?v=U-P7UrLU5qg

Parachute Ejection Test

https://www.youtube.com/watch?v=3CzIlDP5oS8&feature=youtu.be

Before the launch, I tested the system check function for 100 times, and I observed that there were 2 misjudgments. After researching, I believed the misjudgments are caused by the static electricity. I used digital pin to communication between modules. HIGH means safe and LOW means danger. The static electricity might cause the Arduino sense HIGH even the actual situation is LOW. The solution is adding resistant that connects the pin to ground. Since it was impossible to change the design at that time and the rate at which it would occur was low, I did not do anything with it. However, in the future design, this problem will be avoided.

Launch Analysis

Overall, the launch was not perfect, but it has proved that the Fail-Safe function is successful in an unexpected way. Since what happened in the launch is extremely complicated. In the following section, I will list the conclusion and future improvements first and then list the evidences and reasoning procedure.

Conclusion

Success

(1) Recovery subsystem works properly
(2) Altitude algorithm is perfect
(3) Fail-Safe algorithm is successful, but it can be improved.
(4) Rocket design was excellent, nearly no rotation during ascent.
(5) Separation detection method works properly

Failure

(1) IMU module fails at high speed and this trigger the fail-safe mechanism in

unexpected way.

(2) First stage ejected parachute too early.

(3) Mosfect circuit connection is not completely correct.

Future Improvement

(1) First stage avionics should add the Fail-Safe algorithm. For example, I can make the system execute the apogee detection function only after the first stage burnout. This can avoid the unexpected pressure change from causing parachute to be ejected too early.

(2) I should change the IMU, and introduce a land detection function for the future system. In addition, all digital pins can only be turned off after landing.

(3) I should use the correct way to use Mosfect.

(4) All input pins must add resistant that connects pin and ground to avoid static electricity from causing misjudgment.

Flight Data and Videos

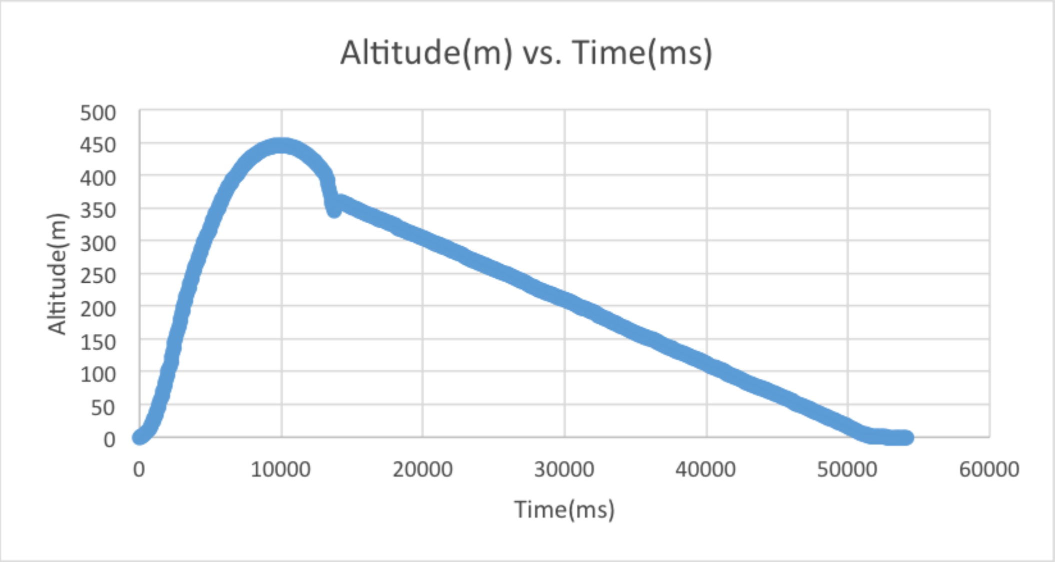


Figure 14 Altitude vs. Time

Figure 14 uses raw data recorded during the test. The curve is very smooth. The only disturbance happened when the parachute was ejected. This plot shows the altitude algorithm is perfect. Kalman filter succeeded in filter the noise.

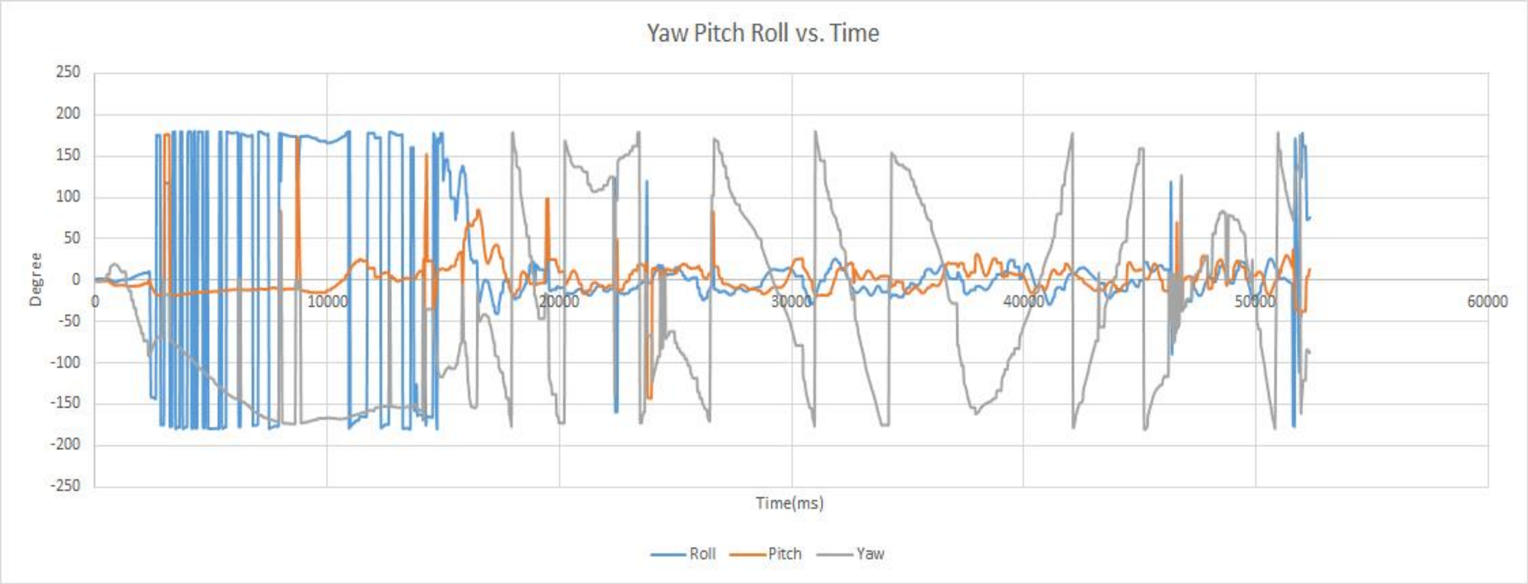


Figure 15. Euler Angles vs. Time

Coordinate System Definition on the right

Euler Angles are hard to imagine, thus I wrote a Processing code to visualize the orientation. In addition, I also wrote a Matlab code to visualize the altitude vs. Time. I embedded visualized data into the video for analysis.

Even without the data visualization, it is clear that the roll during the ascent phase was wrong. It always kept at +179 or -179 degree, which is impossible.

Figure 16. Locate rocket through google map

I had received the landing site coordinate in my computer. I entered coordinate to google map to find the rocket. This showed the recovery subsystem works properly.

Launch Video

https://www.youtube.com/watch?v=1axtpZN-zcI

Video for Analysis

On Board View:

https://www.youtube.com/watch?v=dqz-KwQtJ7I

Tracking View:

https://www.youtube.com/watch?v=8yOUcjnCmQ4

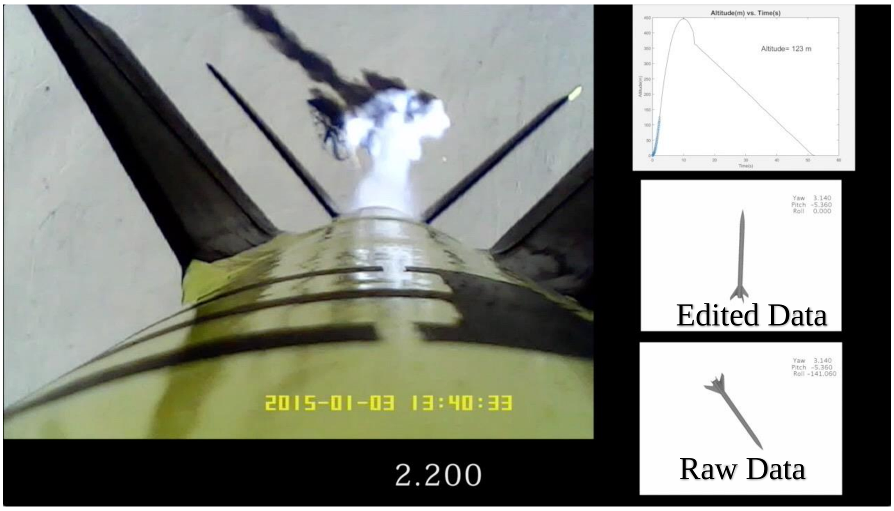


Figure 17. On Board View Description

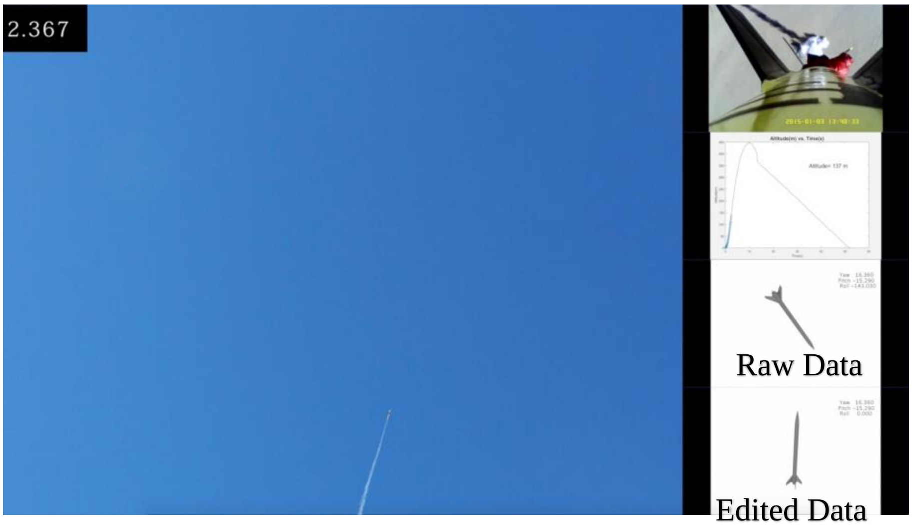


Figure 18. Tracking View Description

Failure Analysis Part 2

Brandon had mentioned the failure analysis of 1st stage. In the following, I focus on the analysis of 2nd stage.

Observations from videos

(1) First stage eject parachute during ascent, and it caused an unexpected separation.
(2) Second Stage did not ignite
(3) Second stage ejected parachute after passing apogee
(4) Separation charge did not be ignited.

The reasoning result must be able to explain all of these observations.

Step 1:

We start form the observation that second stage did not ignite. There are three possible situations.

1. Ignition wiring was broken
2. Electric match malfunction
3. Emergency case (refer to flow chart)

For situation 1, we conducted continuity check to ignition wiring after recovery of the rocket. As it turned out, wiring is in good condition.

Figure 17. Continuity Check

For situation 2, we use the 12V power source (we had proof the system can ignite the match before, so 12V is acceptable) to ignite the electric match for ignition after recovery of rocket and it was successful, which meant the electric match was good.

Step 2:

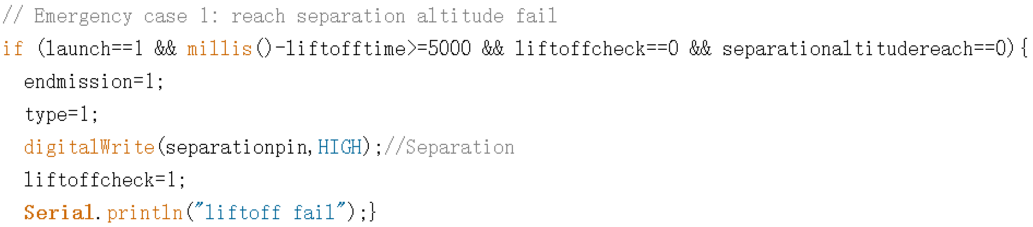
By remove the possibility of situation 1 and 2, the system must enter the emergency case. Now the problem is which emergency case?

Case 0 :

Case 0 was clearly impossible because if it happened all programs would stop.

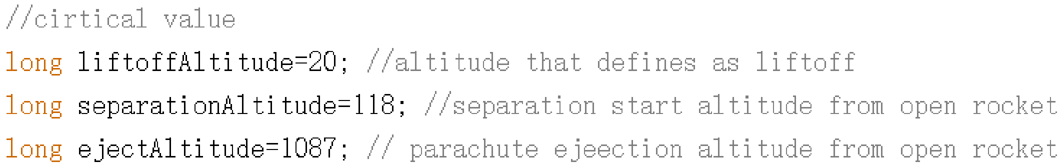
Case 1:

Case 1 is also impossible. The requirement of case 1 is that rocket fails to reach separation altitude within 5 seconds after liftoff.



```
// Emergency case 1: reach separation altitude fail
if (launch==1 && millis()-liftofftime>=5000 && liftoffcheck==0 && separationaltitudereach==0){
  endmission=1;
  type=1;
  digitalWrite(separationpin,HIGH);//Separation
  liftoffcheck=1;
  Serial.println("liftoff fail");}
```

In my code, the separation altitude is 118m.



```
//cirtical value
long liftoffAltitude=20; //altitude that defines as liftoff
long separationAltitude=118; //separation start altitude from open rocket
long ejectAltitude=1087; // parachute ejeection altitude from open rocket
```

From the screen shot of analysis video, the rocket had reached separation altitude in

Clearly, the criteria for case 1 were not met.

Summary: The criteria for case 1 were not met.

Case 2:
For the second situation of case 2, we removed the possibility of there being a separation sensor wiring failure by using the system check after the recovery of rocket. The system check showed all components were in good condition. The first situation of Case 2 seems like the most possible case because the 1st stage ejects the parachute too early. However, the separation charge not being ignited was extremely strange. Let's look at figure 13: 2nd stage flow chart. In my logic, after liftoff, no matter what happens, separation charge will be ignited. However, it did not.

There are two possible situations to explain this unusual phenomena.

1. Separation wiring failure
2. Electric match malfunction.

By using the same method that we used in ignition system, we removed these two possibilities. It was extremely strange, because it should not have happen.

By re-examining my code and schematic, I found another possible situation. My Mosfect circuit connection was not completely correct. Indeed, it works. However, it cannot fully open the Mosfect, and thus the current is limited and small. It takes around 200ms to set off the electric match. If the time was less than 200ms, the electric match would not be ignited.

Now there are three possible situations to explain this unusual phenomena.

1. Separation wiring failure
2. Electric match malfunction.
3. Current running time less than 200ms

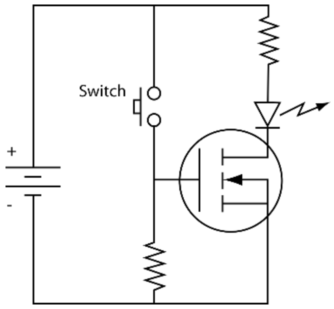


Figure 18. Correct Mosfect Connection

In my code, if emergency case 1 or 2 happened, separation Mosfect would be turned on immediately. It would be turned off only if the rocket had passed the apogee. The time between separation and apogee is obviously greater than 200ms, so situation 3 was impossible. Since case 2 cannot explain why the separation charge did not be ignited, case 2 is impossible.

```
 // Emergency case 1: reach separation altitude fail
 if (launch==1 && millis()-liftofftime>=5000 && liftoffcheck==0 && separationaltitudereach==0){
   endmission=1;
   type=1;
   digitalWrite(separationpin,HIGH);//Separation
   liftoffcheck=1;
   Serial.println("liftoff fail");}
```

```
//Emergency Case 2: sensor fail
if (sensorok==0 && endmission==0){
       endmission=1;

       digitalWrite(separationpin,HIGH);//Separation
       type=1;
       Serial.println("Sensor fail");
    }
```

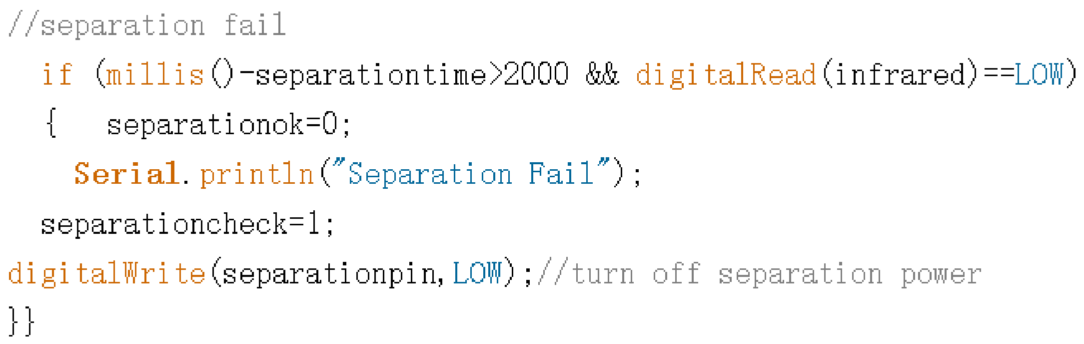
```
//Emergency case procedure
   if(endmission == 1)
   { switch(type){
     //System is not ready
     case 0:
     recovery();
     break;

     case 1:
     //Emergency case 1 and 2.
     //In these cases separation occurs first, after passing apogee,
     //separation power is turned off
     if (apogeereach==0){
      if (currAltitude<lastAltitude)
     {
       measureapogee = measureapogee - 1;
       if (measureapogee== 0)
       { Serial.println("Apogee Reach");
       digitalWrite(separationpin,LOW);//turn off separation power
```

Summary: If it entered case 2, separation charge would be ignited.

Case 3:

If the emergency Case 3 (separation failure) happened, separation power would be immediately turned off. However, the duration between separation and separation failure is 2s, which is long enough to set off the electric match. If the separation charge did not ignite, the only two possible situations are the situations that we have mentioned in Case 2. We have proof they were impossible in Case 2.

Therefore, Case 3 is impossible.



```
//separation fail
  if (millis()-separationtime>2000 && digitalRead(infrared)==LOW)
  {   separationok=0;
    Serial.println(″Separation Fail″);
  separationcheck=1;
digitalWrite(separationpin,LOW);//turn off separation power
}}
```

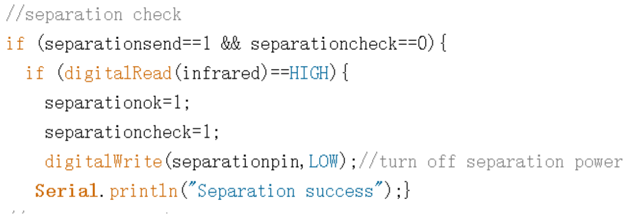
Summary: If it entered Case 3, separation charge would be ignited.

Case 4:

The emergency case is most likely to be Case 4. Let’s try to see whether Case 4 can explain all observations.

The emergency Case 4 only occurs after the success of separation.

In my code, if the separation was successful, separation power would be immediately turned off.



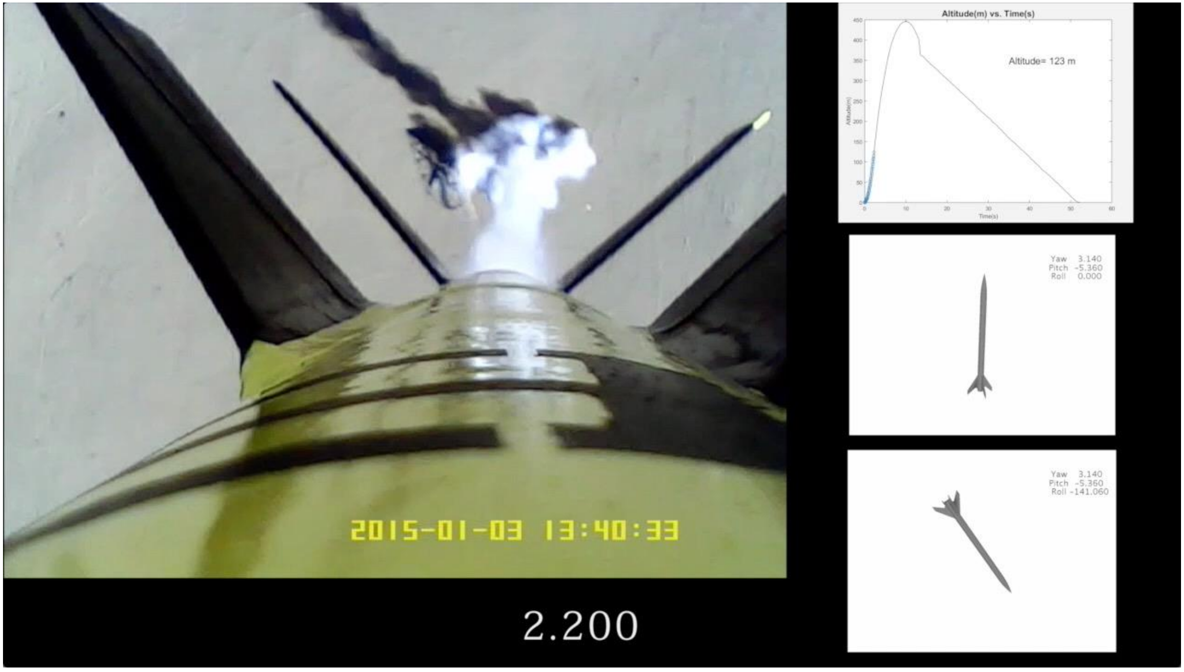
```
//separation check
if (separationsend==1 && separationcheck==0){
  if (digitalRead(infrared)==HIGH){
    separationok=1;
    separationcheck=1;
    digitalWrite(separationpin,LOW);//turn off separation power
   Serial.println(″Separation success″);}
```

It is possible that the time between mosfet on and off is less than 200ms.

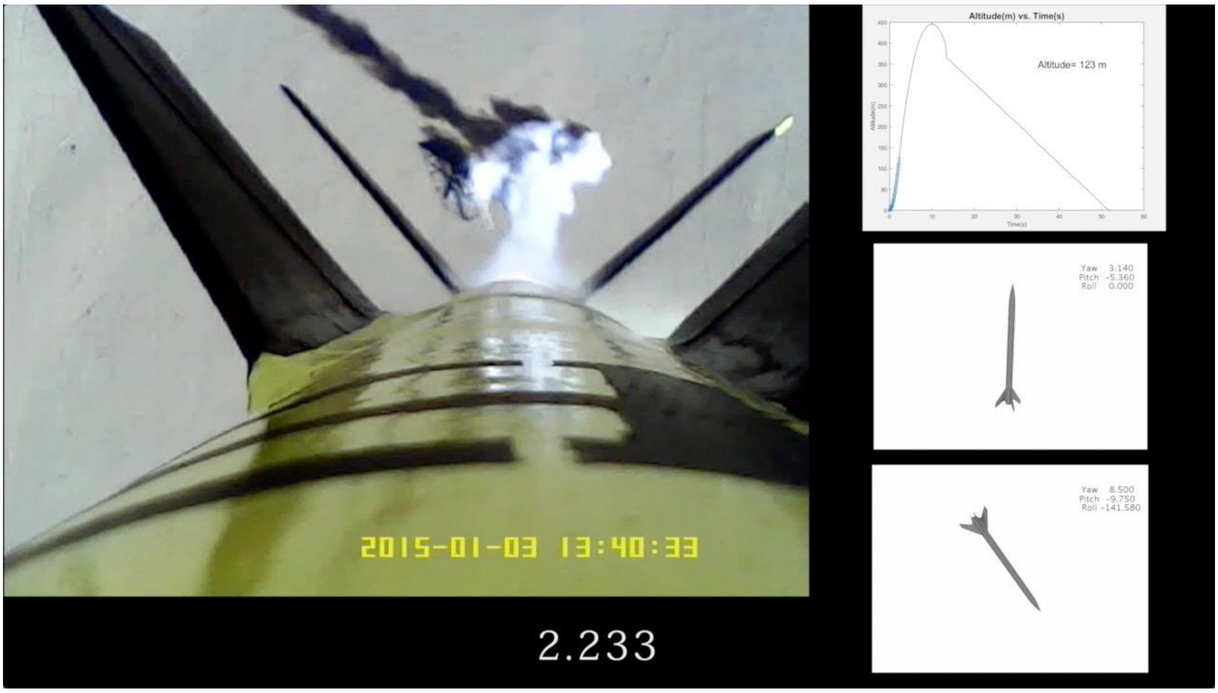
Let's follow the flow chart and analysis video to see what happened.

1. At 2.167s after liftoff, first stage set off the parachute ejection charge.

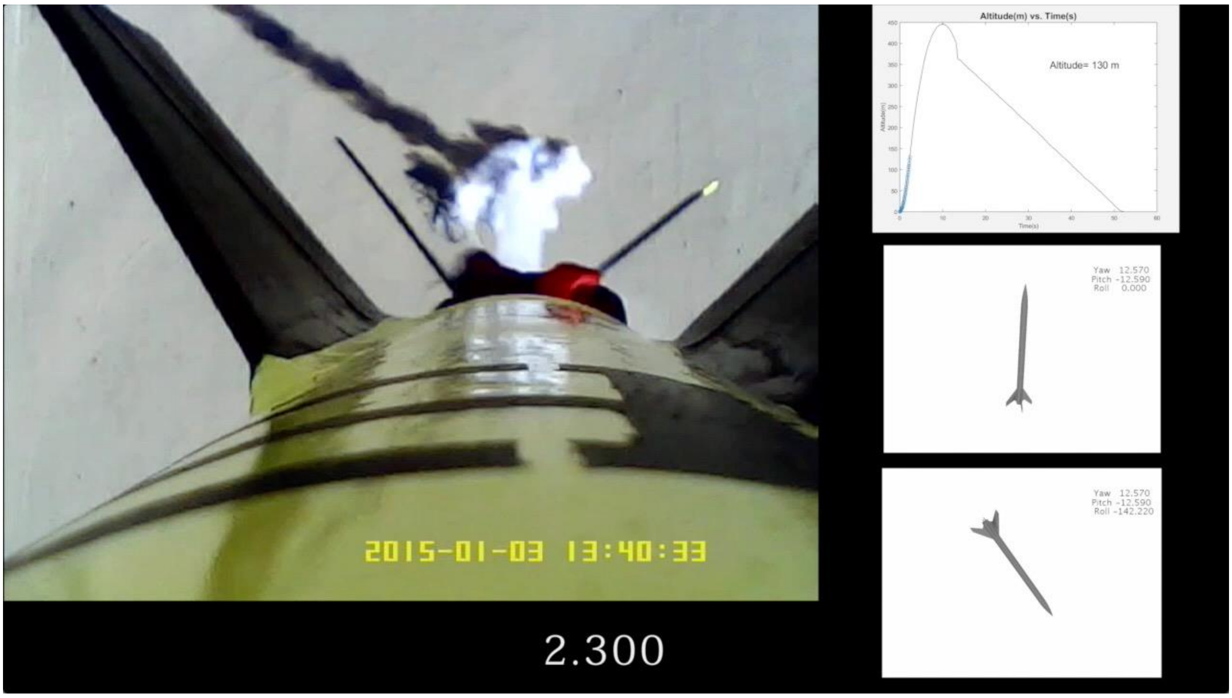
2. At 2.2s after liftoff separation altitude had reached. (separation altitude:118m)



3. At 2.33s after liftoff, system turned on the separation Mosfect.



4. At 2.3s after liftoff, separation was complete and separation Mosfect was turned off. (Keep in mind that this separation was caused by the first stage parachute ejection)



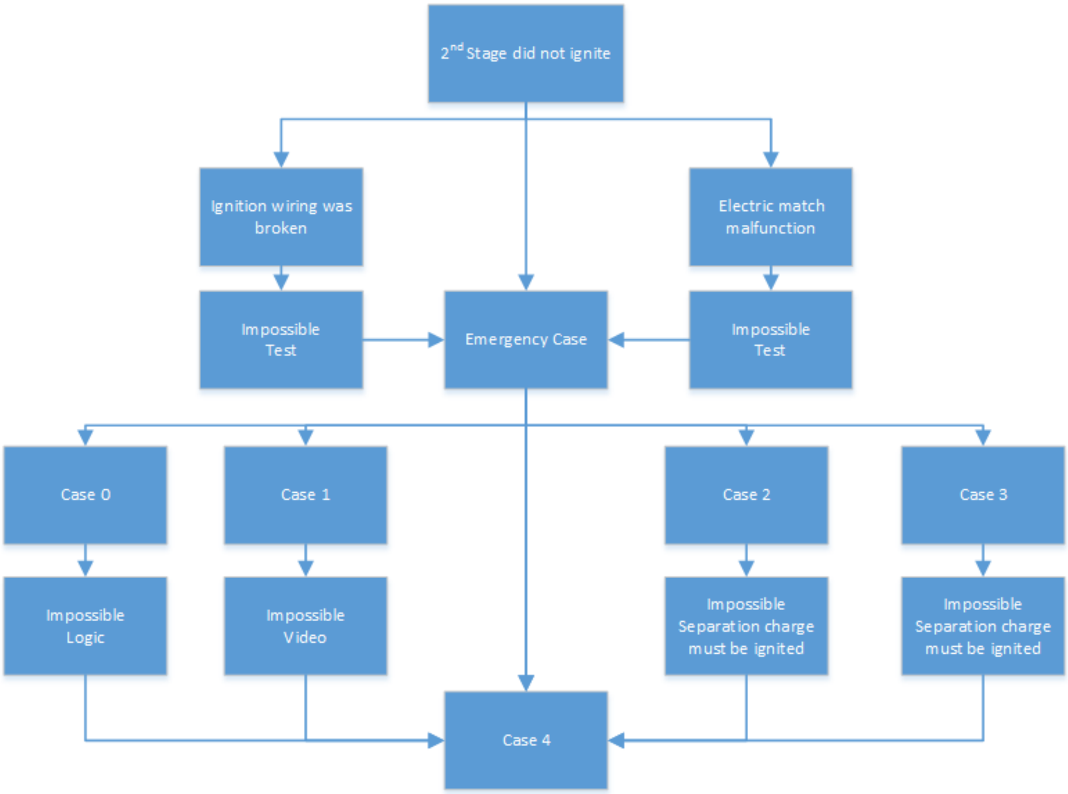
To sum up, the first stage set off the ejection charge around 33ms before the second stage turned on the separation Mosfect. The second stage detected a successful separation and turned off separation Mosfect 67 ms after turning on the separation Mosfect. **The 67 ms current running time is not enough for the electric match to be set off. This explains why the separation charge did not ignite.**

After the successful separation, the second stage avionics started detecting orientation.

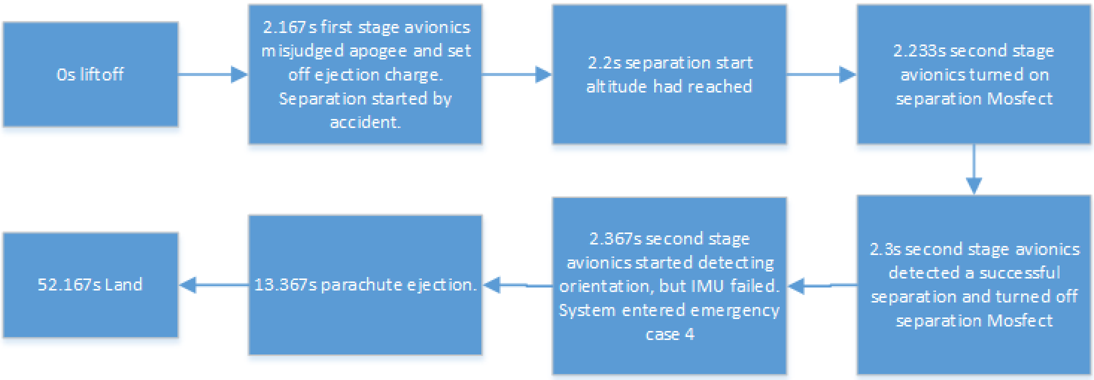
5. System started detecting orientation, however, the IMU failed at this time. The roll was -143.03 degree. The system believed the orientation was dangerous and thus entered the emergency case 4. The second stage did not ignite. The Rocket ejected parachute after passing apogee.

This situation can explain all observations. I believed this was what happened during the launch.

Reasoning Procedure Summarize



Major Events:



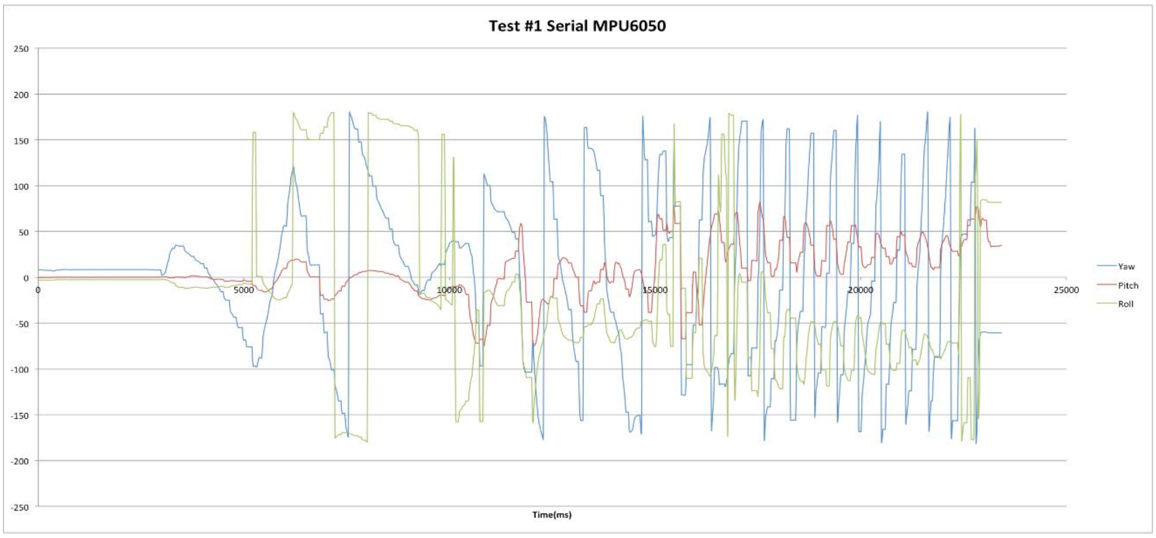
First stage parachute ejection occurred almost at the same time as the second stage executed separation command. When the second stage detected the successful separation, it believed the successful separation was caused by its separation charge and then turned off the separation power. This misjudgment caused the current running time in electric match was not long enough to set off the match and thus separation charge was not set off. Then the system started to detect orientation. However, IMU failed at high speed. Until the rocket had passed the apogee, IMU outputted dangerous roll angle continuously. System

used the wrong IMU data and believed the orientation was dangerous. The second stage stopped igniting and ejected the parachute after passing apogee.

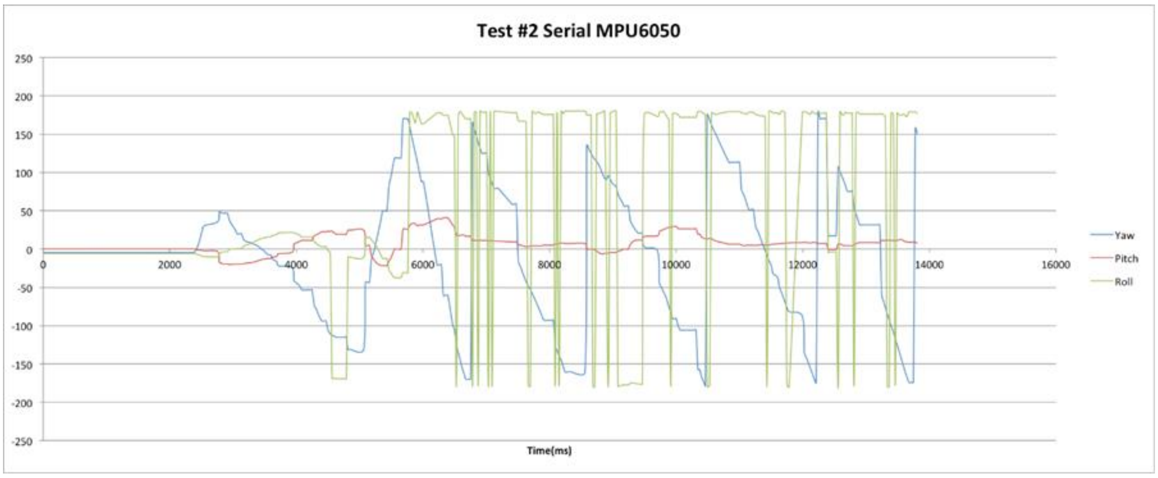
Failure Analysis of IMU

There might be two possible reasons for the failure of IMU. First, there was a malfunction in the IMU that I used in system. Second, serial MPU6050 is not suitable for use at high speed application. If the reason is the second one, I need to find out a substitution. The best way to find out the reason is through testing. I bought a two-stage model rocket and made a tiny avionics that contained two IMU and two data loggers. One IMU is serial MPU6050. Another one is GY-85, the substitution. I launched the test rocket twice. The following is the test results.

Coordinate System

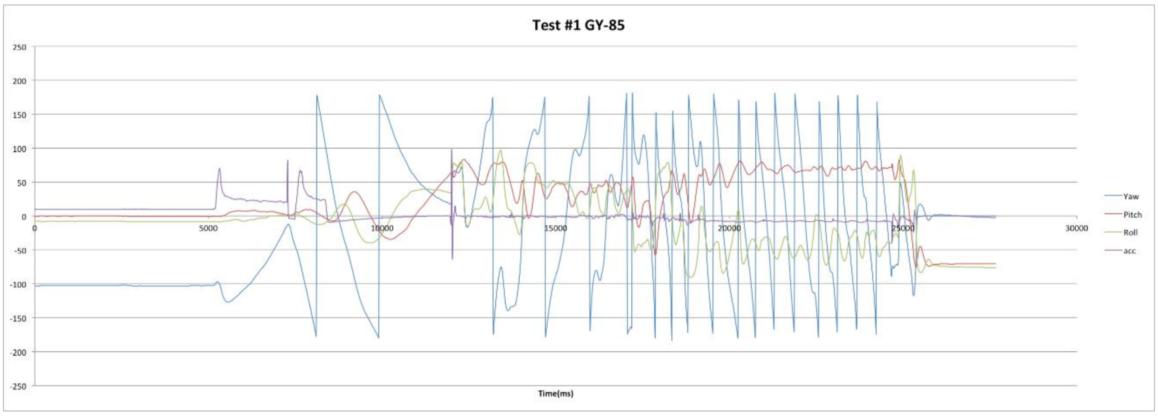


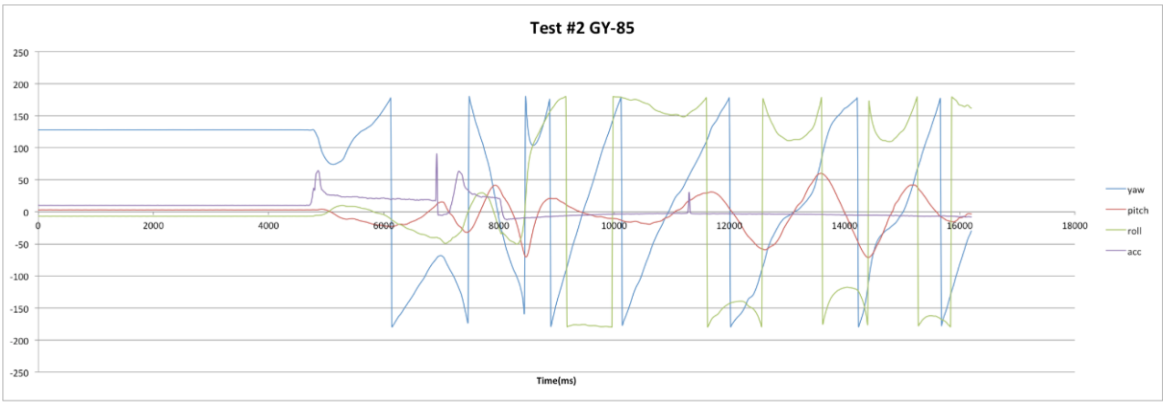
This is the data from sensor test rocket launch #1. During the high speed ascent, the roll data was incorrect as well.



This is the data from sensor test rocket launch #2. The roll data was incorrect as well.

From the above two plots, **we can draw a conclusion that Serial MPU6050 cannot be used in a high speed situation.**





These two plots are data from the new IMU. The data looks correct. From test #1, the parachute was ejected when the pitching angle neared 90 degrees, which is desirable. From the acceleration data, it is easy to see the first stage ignition and separation as well as the second stages ignition and parachute ejection. **We can conclude that this IMU (GY-85) can be used in the future fail-safe system.**

2nd Chance Part 2

The first generation fail-safe system records the flight data, but it does not record flight events. Therefore, I spent a lot of time figuring out which events happened and when they happened. Another problem is the amount of data that I collected. The system starts recording when the power is on, and it stops recording when powered off. Therefore, I spent a lot of time finding the useful data. Using a Micro SD card is not a good method for data recording either. The Micro SD card might be ejected due to the collision or vibration. This happened when I did the IMU sensors test flight. The fail-safe algorithm also needs to be improved. I should use both the IMU and barometric sensor to make decisions. At least, I should use simulation results to assist decision. I should also use the correct Mosfect circuit connection. In addition, the IMU needs to be changed. Lastly, all input pins should add resistance to remove the possibility of misjudgment caused by static electricity.

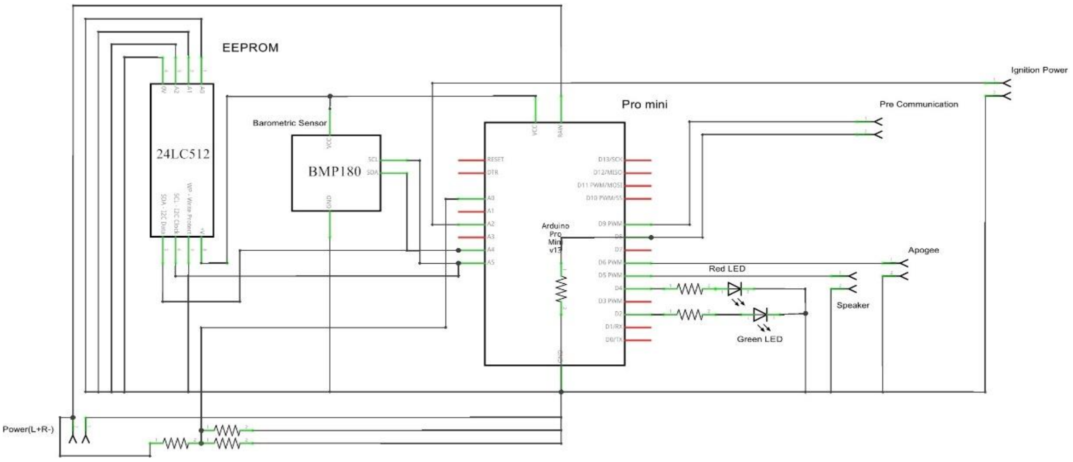
The second generation fail-safe system has an internal events recorder. It stores all important events such as liftoff, apogee, and emergency case number in the Arduino's internal EEPROM. It stores all flight data in external EEPROM. The EEPROM does not have any mechanical structure, so it is safe. It starts storing data when it detects liftoff and stops recording when it detects landing. In addition, 6 to 20 sets of data before liftoff will also be stored.

The second generation system has a more complicated fail-safe algorithm, and it uses a module design. It has four modules: recovery module, main module, attitude module, and barometric module. It can be used in either one or two stages of the rocket. In the two stages application, it uses barometric sensor, IMU, and simulation results to make decisions. In one stage application, it also uses at least two factors to make decisions. GPS module and main module share the same telemetry device. Before system check results outputting and after landing, the GPS will send current coordinate. During the flight, telemetry devices will send the major events to ground station. The Mosfect circuit was redesigned. I used the correct connection and an optocoupler to completely isolate the main power circuit and ignition power circuit. It also adds the battery power check function to system check. The detail report will be provided after the test flight.

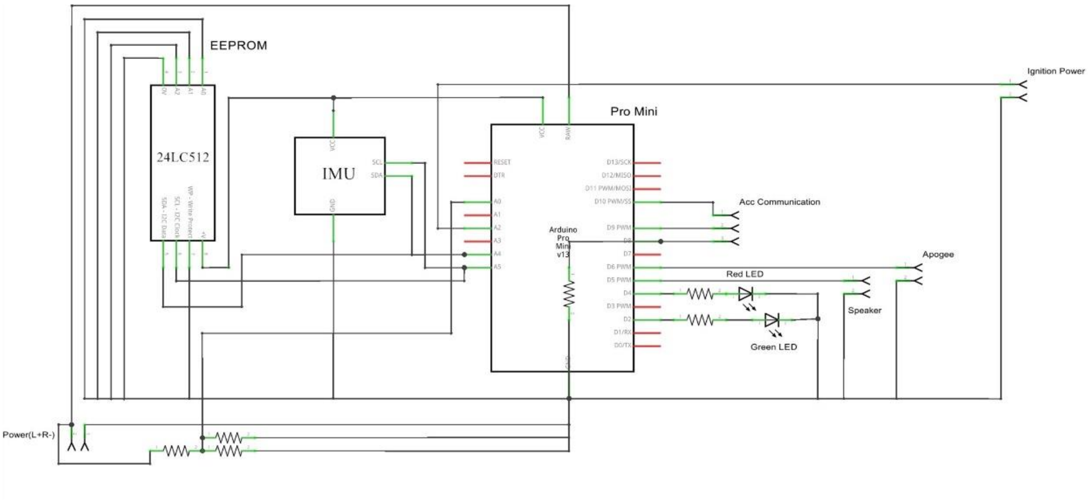
Second Generation Fail-Safe System Module Selection Description

One Stage	Two Stages
Attitude Module	N/A
Barometric Module	N/A
Attitude Module+ Barometric Module+ Main Module	Attitude Module+ Barometric Module+ Main Module
Attitude Module+ Barometric Module+ Main Module+ Telemetry Device	Attitude Module+ Barometric Module+ Main Module+ Telemetry Device
Attitude Module+ Barometric Module+ Main Module+ GPS Module+ Telemetry Device	Attitude Module+ Barometric Module+ Main Module+ GPS Module+ Telemetry Device

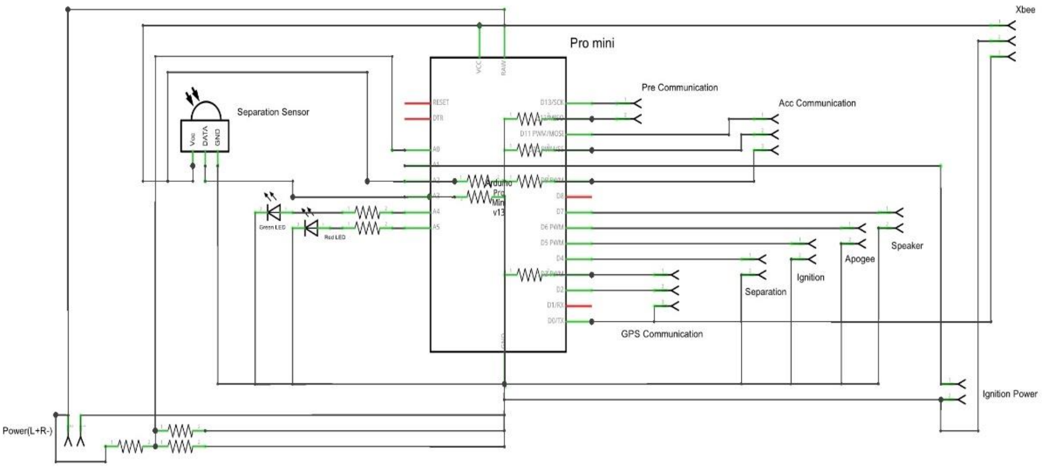
Schematic



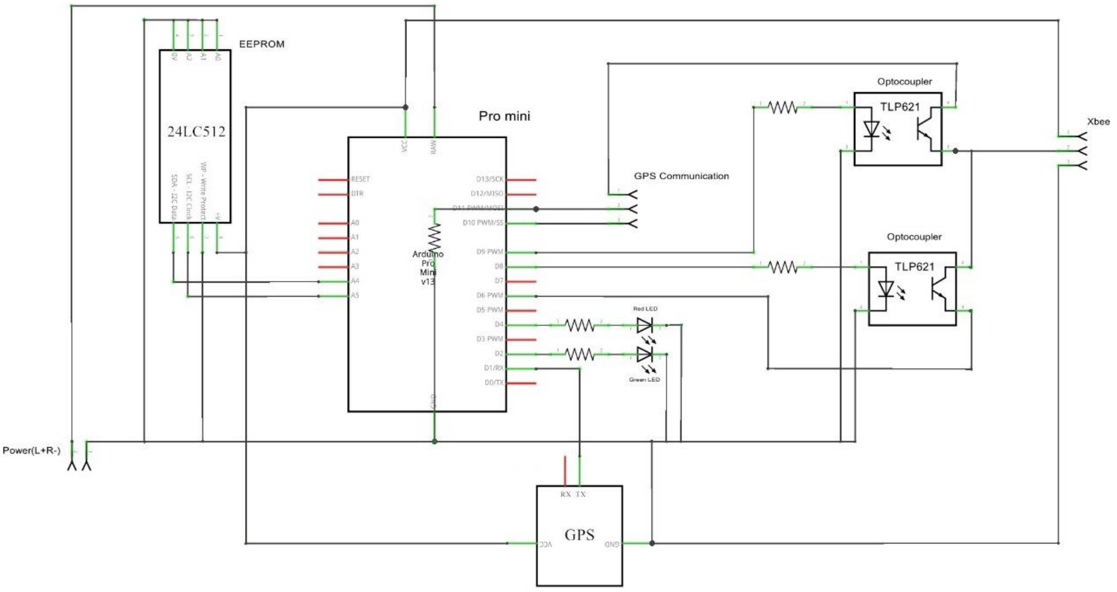
Barometric Module



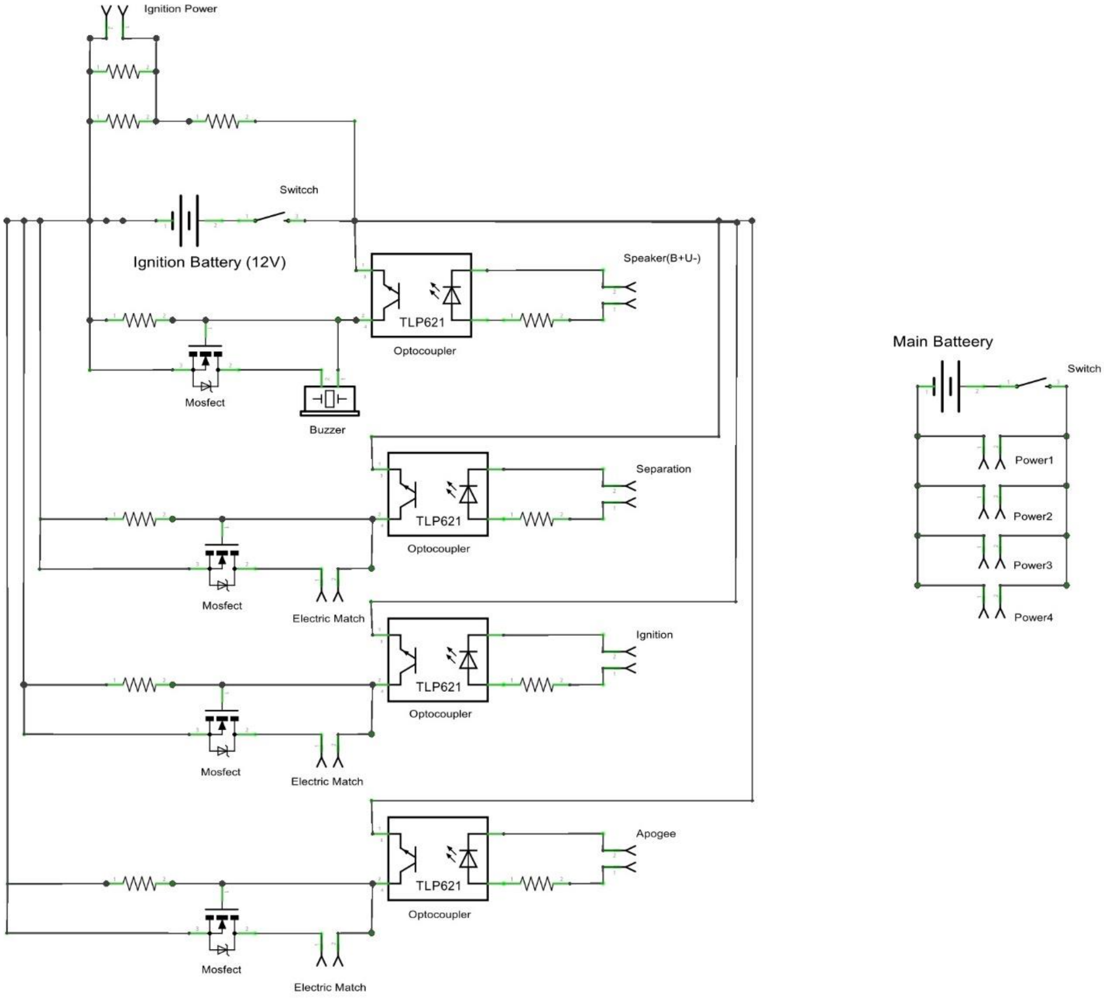
Attitude Module



Main Module



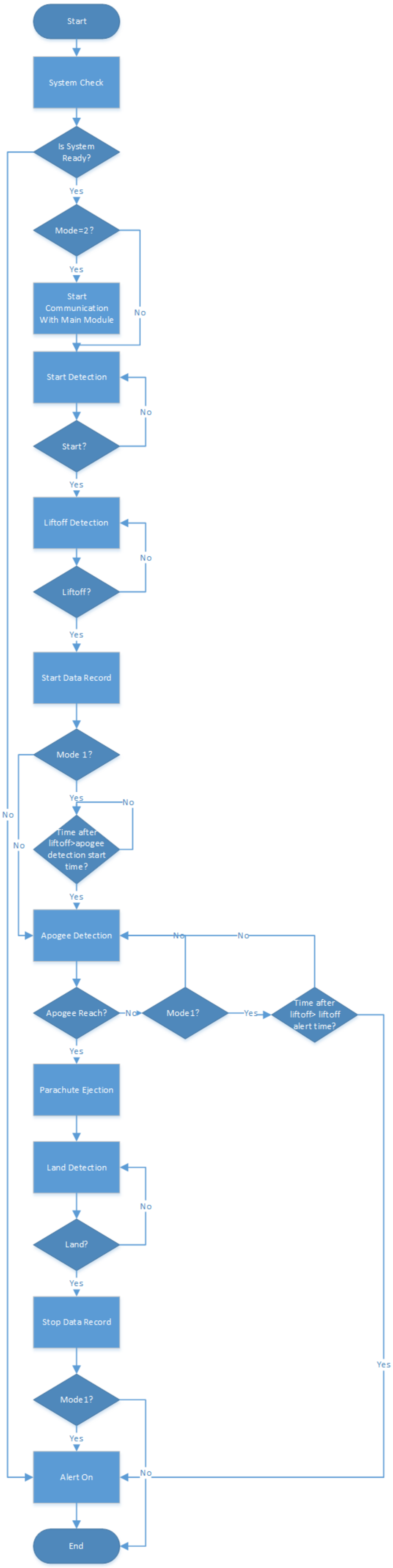
GPS Module



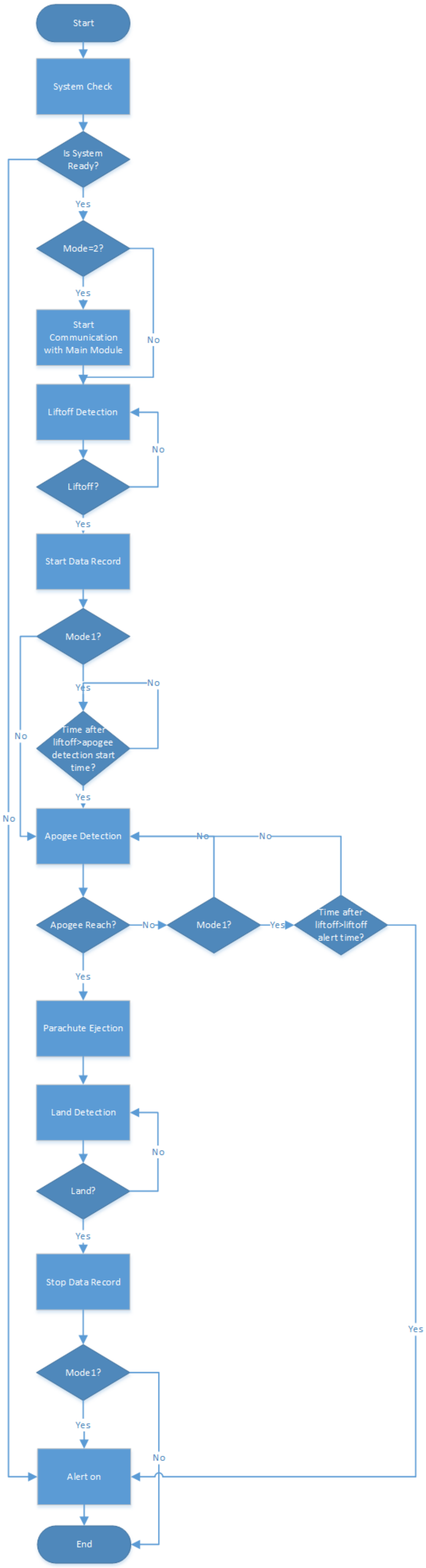
Accessory

Flow Chart

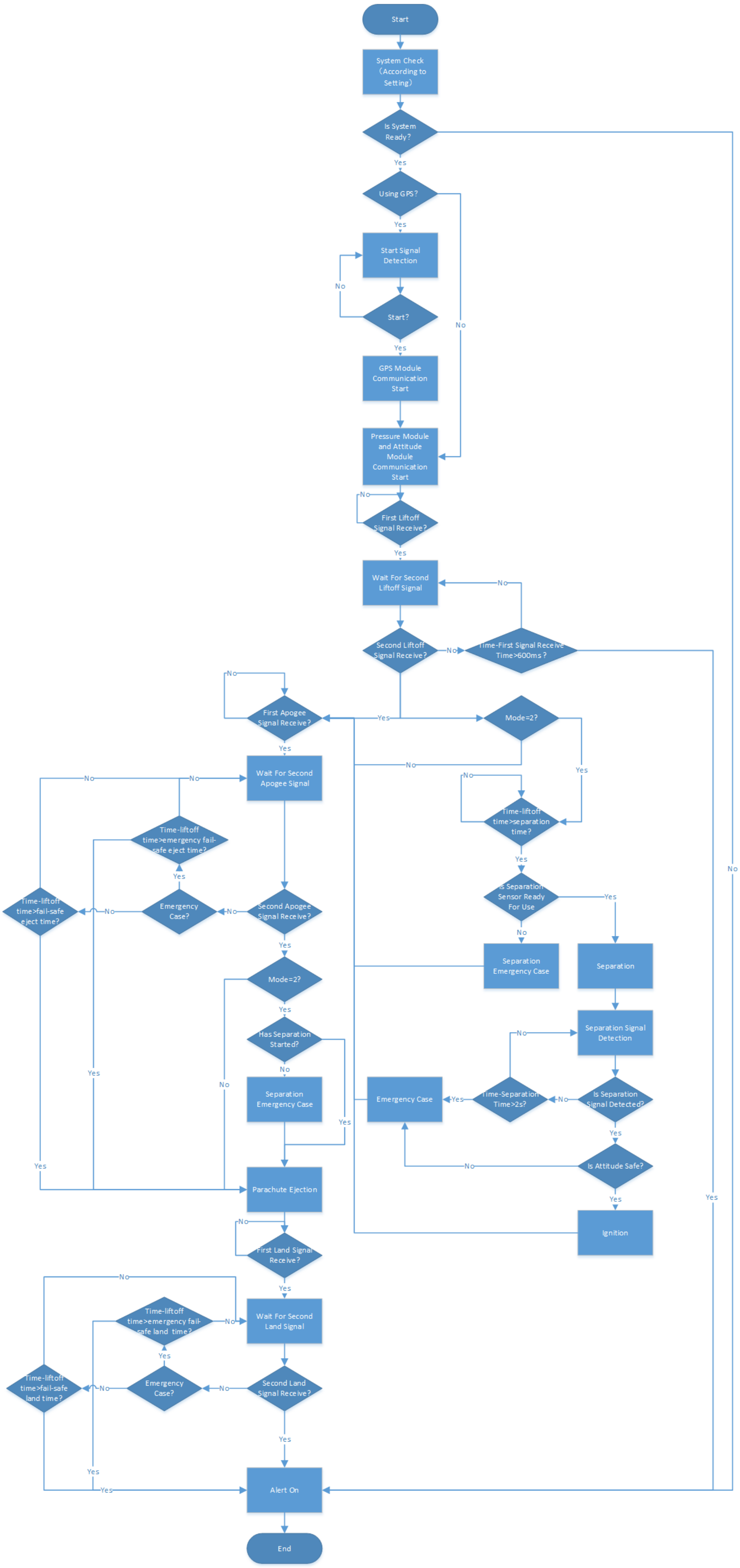
Barometric Module



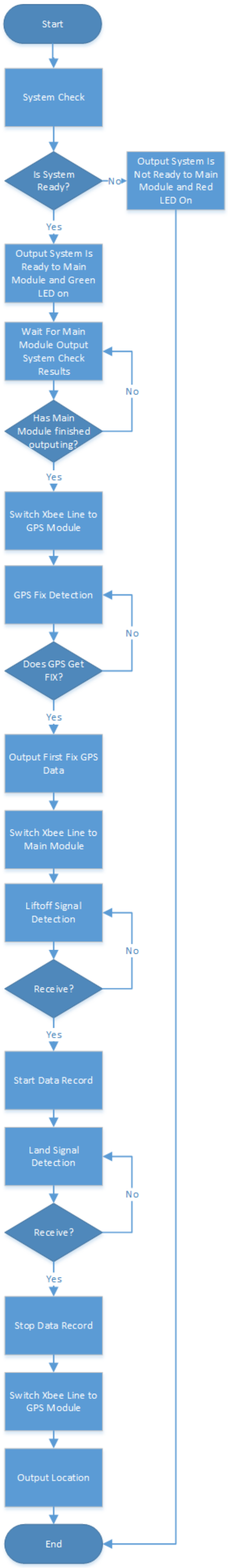
Attitude Module



Main Module

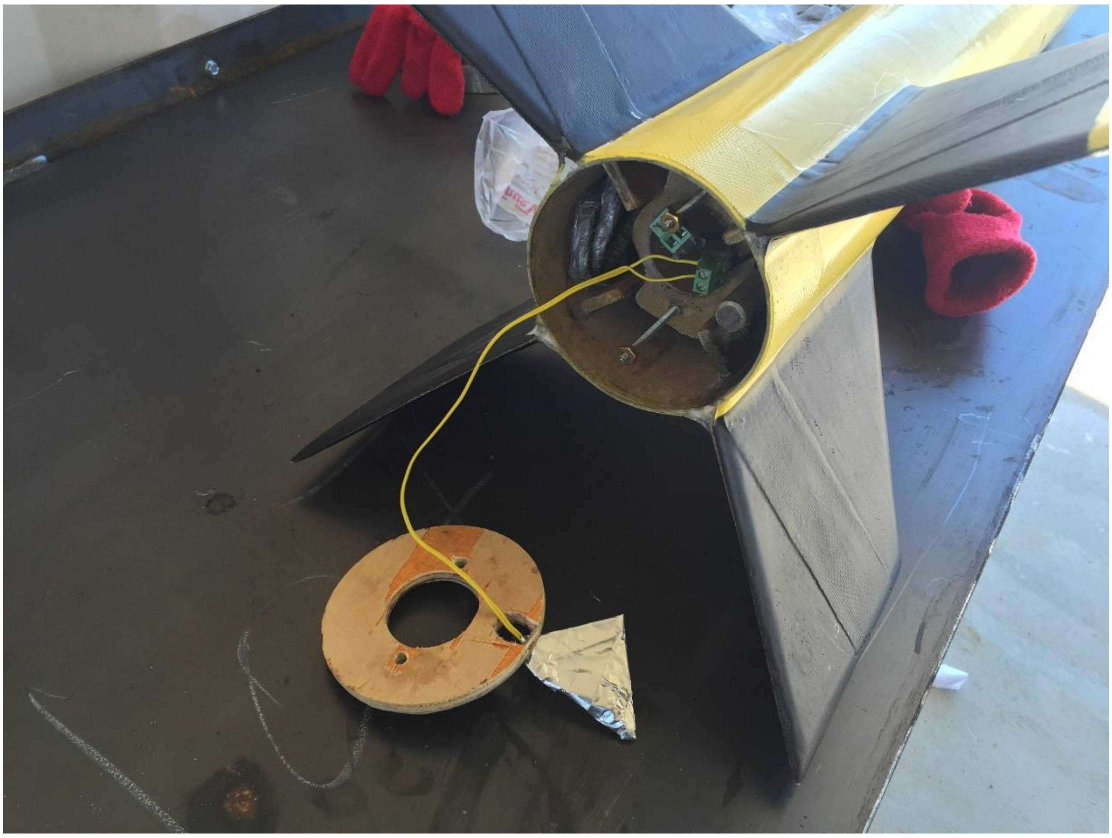

Start
System Check（According to Setting）
Is System Ready?
Yes
No
Using GPS?
Yes
No
Start Signal Detection
Start?
No
Yes
GPS Module Communication Start
Pressure Module and Attitude Module Communication Start
First Liftoff Signal Receive?
No
Yes
Wait For Second Liftoff Signal
Second Liftoff Signal Receive?
No
Time-First Signal Receive Time>600ms?
No
Yes
Mode=2?
Yes
No
Time-liftoff time>separation time?
No
Yes
Is Separation Sensor Ready For Use
Yes
No
Separation Emergency Case
Separation
Separation Signal Detection
Is Separation Signal Detected?
No
Time-Separation Time>2s?
No
Yes
Emergency Case
Yes
Is Attitude Safe?
No
Yes
Ignition
First Apogee Signal Receive?
No
Yes
Wait For Second Apogee Signal
No
No
Time-liftoff time>emergency fail-safe eject time?
Yes
Second Apogee Signal Receive?
No
Emergency Case?
No
Time-liftoff time>fail-safe eject time?
Yes
Yes
Yes
Mode=2?
Yes
No
Has Separation Started?
No
Yes
Separation Emergency Case
Parachute Ejection
First Land Signal Receive?
No
Yes
Wait For Second Land Signal
No
Time-liftoff time>emergency fail-safe land time?
No
Yes
Second Land Signal Receive?
No
Emergency Case?
No
Time-liftoff time>fail-safe land time?
Yes
Yes
Yes
Alert On
End

GPS Module


Start
System Check
Is System Ready?
No
Output System Is Not Ready to Main Module and Red LED On
Yes
Output System Is Ready to Main Module and Green LED on
Wait For Main Module Output System Check Results
No
Has Main Module finished outputing?
Yes
Switch Xbee Line to GPS Module
GPS Fix Detection
No
Does GPS Get FIX?
Yes
Output First Fix GPS Data
Switch Xbee Line to Main Module
Liftoff Signal Detection
No
Receive?
Yes
Start Data Record
Land Signal Detection
No
Receive?
Yes
Stop Data Record
Switch Xbee Line to GPS Module
Output Location
End

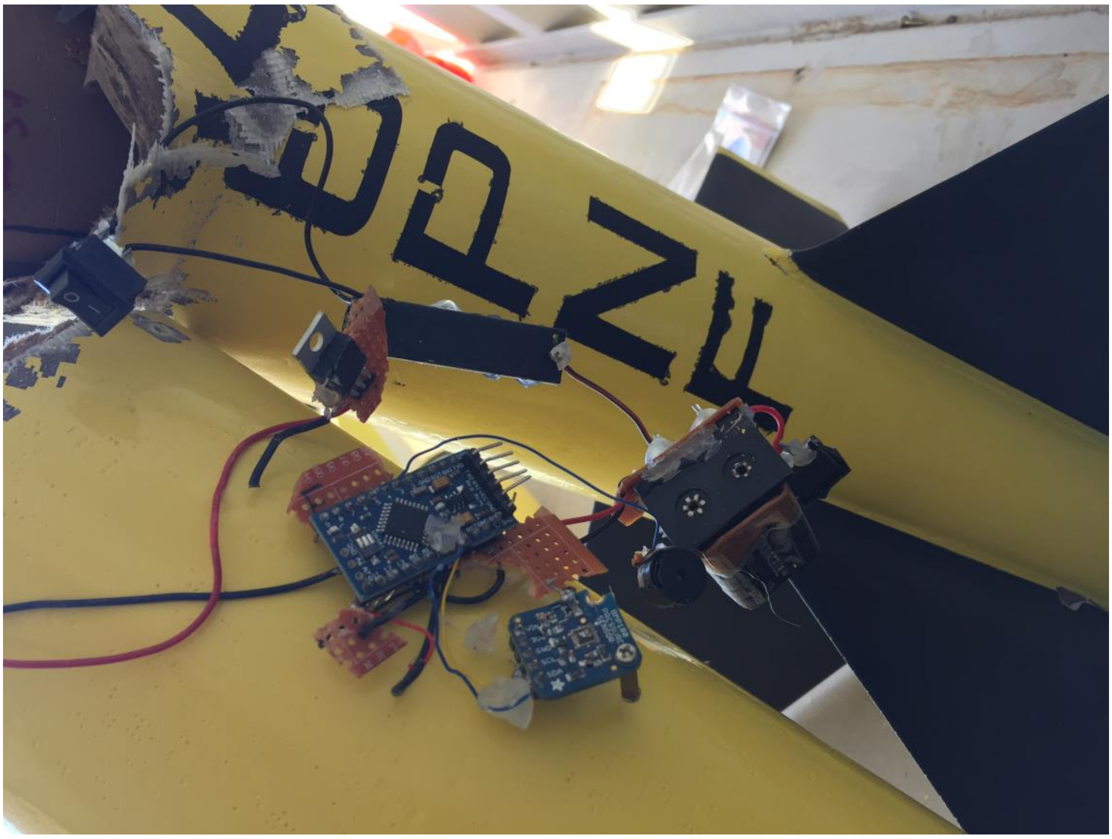
Appendix

Liftoff



Separation Charge Connection

First Stage Wreckage



First Stage Avionics Wreckage

Yuan Zhang with Rocket

Brandon Hernaez and Yuan Zhang with Rocket