

# Rocket Payload Team Final Report

Darrell Adams, Annalise Arroyo, Holden Brown, Eric Dollinger, Wesley Garrison

May 7, 2020



# 1 Table of Contents

<b>1 Table of Contents</b>	2
<b>2 Introduction</b>	4
<b>3 Detailed System Requirements</b>	6
<b>4 Detailed project description</b>	8
4.1 System theory of operation	8
4.2 System Block diagram	11
4.3 Subsystem Descriptions	12
4.3.1 Subsystem 1: Motor System	12
4.3.1.1 Motor Overview	12
4.3.1.2 Motor Testing	13
4.3.2 Subsystem 2: Power Management System	14
4.3.2.1 Power Overview	14
4.3.2.2 Power Testing	14
4.3.3 Subsystem 3: Sensor System	14
4.3.3.1 Sensor Overview	15
4.3.3.2 Sensor Testing	16
4.3.4 Subsystem 4: Communication System	16
4.3.4.1 Communication Overview	17
4.3.4.2 Communication Testing	17
4.3.5 Subsystem 5: Microcontroller Intelligence System	18
4.3.5.1 Microcontroller Overview	18
4.3.5.2 Microcontroller Testing	20
4.3.6 Subsystem 6: Retention System	22
4.3.6.1 Retention Requirements	22
4.3.6.2 Retention Testing	24
4.4 Interfaces	25
4.4.1 Board Schematics and Board Design	25
<b>5 System Integration Testing</b>	29
5.1 Subsystem Testing:	29
<b>6 Installation manual</b>	31
6.1 How to install your product	31
<b>7 To-Market Design Changes</b>	31
<b>8 Conclusions</b>	33
<b>9 Appendices</b>	34



## 2 Introduction

Our team designed the Rover payload electrical systems for the Notre Dame Rocketry Team which competes in NASA's Student Launch competition. Responsibilities for the electrical system included power management, RF communication, manual control design, and autonomous control design.

The official competition description for 2019-2020 per NASA's website is as follows:

“The NASA Student Launch (SL) is a research-based, competitive, and experiential learning project that provides relevant and cost-effective research and development.”

“Student Launch reaches a broad audience of colleges, universities, and secondary institutions across the nation in an 8-month commitment to design, build, launch, and fly a payload(s) and vehicle components that support NASA research on high-power rockets.

The College/University Division teams are challenged to develop a system capable of collecting a simulated lunar ice sample. Teams may incorporate additional research through the use of a separate payload if desired.”

The Notre Dame Rocketry Team's payload will be required to exit the rocket after a successful landing, navigate to one of five predetermined sample locations that are each 3 feet in diameter with a colored tarp 10 feet in diameter surrounding the sample area, and collect at least 10 mL of a simulated lunar ice that could be as much as two inches below the ground. After the sample is recovered, the payload vehicle must transport the sample at least ten linear feet away from the chosen recovery area. Any hardware that is used to collect the sample must be launched with the rocket.

This year, the team's payload design consists of a Rover primary payload and UAV secondary payload. The UAV was used to first fly to the sample and provide GPS coordinates of the sample to the Rover and ground station. The Rover would then use either autonomous control, using the sensors included to navigate to the coordinates, or manual control, where a controller would give the Rover commands from the ground station. As our team is focusing on the electrical design of the rover, this report will not go into detail about the mechanical design of the rover or the details of the UAV. These details can be found in the NDRT technical reports found on our website or the NDRT AIAA website also linked from our website.

Due to the Coronavirus and subsequent national health crisis, our team was unable to fully implement, test, and launch our design due to supply chain issues in the first half of the semester and the closing of campus in mid-May. However, to the point that we were able to complete, our design met the majority of our expectations. In the few short months that we were together on campus, we designed and tested our proposed custom printed circuit board with satisfactory results. We successfully implemented the RF communication necessary for the Rover to communicate with the Rocketry Team ground station and UAV with a range that exceeded our requirements. We were also able to successfully interface with each sensor necessary for autonomous control of the Rover. The only aspect of our project that was not implemented and tested was the integration of the separate subsystems and autonomous control, including testing with the mechanical body of the Rover.

A budget of project parts can be found in the Appendix, and full budgeting for the Notre Dame Rocketry Team at each stage of the project can be found in the PDR, CDR, and FRR technical reports on both our senior design and the NDRT website.

### 3 Detailed System Requirements

System requirements were based on requirements given by the NASA Student Launch competition, and derived requirements developed with the Notre Dame Rocketry Team.

Requirements with an ID prefix number of 4 were given by NASA, while requirements with a prefix number of P are “Payload” team derived requirements, with a listed parent ID if

applicable. Full NASA Student Launch and NDRT derived requirements can be found in the technical reports uploaded to both our senior design and the NDRT website.

Requirement		Verification Plan	Status
ID	Description		
4	All payload designs must be approved by NASA. NASA reserves the authority to require a team to modify or change a payload, as deemed necessary by the Review Panel, even after a proposal has been awarded.	The team acknowledges that designs must be approved by NASA and that NASA may request design changes.	Complete
4.2	University teams will design a system capable of being launched in a high power rocket, landing safely, and recovering simulated lunar ice from one of several locations on the surface of the launch field. The methods utilized will be at the teams' discretion and will be permitted so long as the designs are deemed safe, obey FAA and legal requirements, and adhere to the intent of the challenge. An additional experiment is allowed, and may be flown, but will not contribute to scoring. If the team chooses to fly an additional experiment, they will provide the appropriate documentation in all design reports so the experiment may be reviewed for flight safety.	The team shall be competing in the university division and shall design a payload which meets the listed requirement. The team shall have discretion to design the payload but shall work with team mentors to verify the design is safe, meets FAA requirements, and adheres to the requirements of the challenge. An additional experiment will be flown (ABS), and is thoroughly documented in Section 3.5.5.	Complete
4.3.1	The launch vehicle will be launched from the NASA-designated launch area using the provided Launch pad. All hardware utilized at the recovery site must launch on or within the launch vehicle.	The launch vehicle will be launched from the NASA designated launch area using the provided launch pad. All hardware utilized at the recovery site shall be launched on or within the vehicle.	Complete
4.3.2	Five recovery areas will be located on the surface of the launch field. Teams may recover a sample from any of the recovery areas. Each recovery site will be at least 3 ft in diameter and contain sample material extending from ground level to at least 2 in. below the surface.	The team shall design the payload to be capable of traveling to one of the recovery areas and recover a sample extending at least 2 in. below the surface. The sample retrieval system will be tested.	In Progress
4.3.3	The recovered ice sample will be a minimum of 10 mL.	The payload will be designed to be capable of recovering an ice sample with a minimum volume of 10 mL and the system will be tested.	In Progress
4.3.4	Once the sample is recovered, it must be stored and transported at least 10 linear ft from the recovery area.	The payload will be designed to be capable of transporting the recovered sample at least 10 linear ft from the recovery area and will be tested.	In Progress

Requirement		Verification Plan	Status
ID	Description		
4.3.5	Teams must abide by all FAA and NAR rules and regulations.	The team shall abide by all FAA and NAR rules and regulations. The team shall conduct a review with the team launch manager prior to the launch day to verify all regulations are met.	Complete
4.3.6	Black powder and/or similar energetics are only permitted for deployment of in-flight recovery systems. Any ground deployments must utilize mechanical systems.	The payload deployment shall utilize an in-flight black powder nose cone ejection system. See Section 4.5.2 for details.	Complete
4.3.7	Any part of the payload or vehicle that is designed to be deployed, whether on the ground or in the air, must be fully retained until it is deployed as designed.	The payload shall be designed to be fully retained until it is deployed as designed. This shall be verified in tests prior to launches and demonstrated during the demonstration flights.	Complete
4.3.7.1	A mechanical retention system will be designed to prohibit premature deployment.	The mechanical system was designed to prohibit premature deployment and has been analyzed using methods such as FEA to determine forces on the system to avoid premature deployment. See Section 4.5.1 for details on the retention system design and analysis.	Complete
4.3.7.2	The retention system will be robust enough to successfully endure flight forces experienced during both typical and atypical flights.	The retention system shall be subjected to shake tests to ensure the system is capable of enduring typical and atypical flight forces while still being reusable per Req. 2.4.	Complete
4.3.7.3	The designed system will be fail-safe.	The retention system is designed to be fail-safe to ensure that failure of any system components does not result in the payload being damaged or released prematurely. The system shall be designed with redundancy and thoroughly tested to avoid failures.	Complete
4.3.7.4	Exclusive use of shear pins will not meet Req. 4.3.7.	The team will not exclusively use shear pins for retention. See Section ?? for retention design details.	Complete
4.4.1	Any experiment element that is jettisoned during the recovery phase will receive real-time RSO permission prior to initiating the jettison event.	The payload will be completely retained during flight and recovery.	Complete
4.4.2	UAV payloads, if designed to be deployed during descent, will be tethered to the vehicle with a remotely controlled release mechanism until the RSO has given permission to release the UAV.	The payload will be completely retained during flight and recovery.	Complete
4.4.3	Teams flying UAVs will abide by all applicable FAA regulations, including the FAA's Special Rule for Model Aircraft.	The team shall abide by all FAA regulations and shall carefully review the regulations during each step of the development process.	Complete
4.4.4	Any UAV weighing more than .55 lbs. will be registered with the FAA and the registration number marked on the vehicle.	The team UAV weighing more than 0.55 lbs will be registered with the FAA and the registration number marked on the vehicle.	In Progress

Requirement		Justification	Verification Plan	Status
ID	NASA Parent ID	Description		
P1		The Rover must not have an overall width larger than 6 in.	Constraining the Rover to a 6 in. maximum width gives the other subsystems a dimension to design around	Complete
P2	4.3.2	The Rover must be able to overcome small obstacles such as rocks, corn stalks, and crop rows.	The terrain where the launch will be conducted is not flat and easy to navigate, so the Rover should be able to overcome any obstacles it may encounter.	In Progress
P3	4.3.2	The Rover must be able to traverse through mud, puddles, corn stalks, and corn fields.	The state of the terrain is variable and the rover should be designed to overcome any terrain it may experience.	In Progress
P4	4.3.2	The Rover must secure all electronics.	As the Rover traverses rough terrain, all electronics must stay in place to remain functioning.	In Progress
P5		The Rover must not weigh more than 40 oz.	The Rover must not contribute more than 40 oz to the overall payload weight budget so that the launch vehicle weight is on target.	Complete
P6	4.3.2	The Rover must have a minimum operating time of 20 min.	A 20 min operating time will provide adequate time for the Rover to traverse to the closest CFEA	In Progress
P7		The Rover must have a manual override switch.	A manual override enables the operator to take control of the Rover should an error occur in the control code.	Complete
P8	2.7	The Rover will remain dormant until receiving the initiation signal from the UAV.	A low power mode will conserve the battery life of the Rover prior to deploying.	In Progress
P9		The UAV must be no larger than 4 in x 4 in.	This constraint enables the UAV to fit inside the payload bay without the need for moving arms.	Complete
P10		The UAV frame must protect the battery.	Damage to the battery can result in catastrophic failure.	Complete
P11		The UAV must weigh under 24 oz.	Constraining the UAV to a maximum weight will prevent the payload from going over weight.	Complete

Requirement					Status
ID	NASA Parent ID	Description	Justification	Verification Plan	
P.12	4.3.2	The UAV must have a minimum flight time of 10 min.	A 10 minute flight time will provide adequate time for the UAV to search the area around the Rover.	Flight time calculations will be conducted at various design milestones to verify the selected components and the selected frame design will enable the UAV to fly for a minimum of 10 min.	In Progress
P.13		The UAV must use a commercial flight controller.	Using a commercially available flight controller expedites the flight software development process	A commercial flight controller for the UAV has been selected.	Complete
P.14		The UAV must have a manual override switch.	A manual override enables the operator to take control of the UAV should an error occur in the flight code	All flight software will be required to have a manual override built into the code.	Complete
P.15	4.3.3	The Sample Retrieval system must recover a minimum sample size of 10 mL	A 10 mL sample collection is required for mission success.	The system has been designed to collect 10 mL of sample. The system will be extensively tested to ensure it consistently retrieves a sample no smaller than 10 mL.	Complete
P.16	4.3.2	The Sample Retrieval system must be able to correctly orient itself for retrieval operations.	A self orienting sample retrieval system will allow the Rover to be in any position while the retrieval system is operating	The retrieval system has been extensively tested to verify it can correctly orient itself to perform the retrieval operations consistently and reliably.	Complete
P.17	4.3.4	The Sample Retrieval system must retain and protect the recovered sample from spillage and contamination.	Securing the sample once it is collected will ensure successful deliver of the sample from the CFEA.	The sample container has been water tested to ensure no contaminants can leak into the container and the container has been tested through sample retrieval simulations to ensure no amount of sample can spill out of the container during the translation of the Rover.	Complete
P.18		The Sample Retrieval system must interface with the Rover electronics.	Reduces system complexity and reduces the risk of failure	The sample retrieval team will communicate regularly with the Rover electronic team to ensure that the retrieval system can integrate into the electronic system of the Rover.	In Progress
P.19		The Sample Retrieval system must be easily integrated with the Rover frame.	Reduces system complexity and reduces the risk of failure	The team is utilizing Fusion 360 and cloud based models to ensure all assemblies use up to date models and all systems integrate together.	Complete
P.20	4.3.7.3	The Deployment system must have multiple fail-safes.	This will ensure system success despite a component failure within the system	All designs of the deployment system will include a minimum of two redundant locking mechanisms for restricting motion of components in the bulkhead of the vehicle. See Section 4.5 for deployment design details.	Complete
P.21		The Deployment system must be able to correctly orient the Rover and UAV regardless of the landing position of the upper section of the vehicle.	The orientation of the Rover is paramount to mission success	The orientation system will be extensively tested with the bulkhead section of the vehicle to ensure that it consistently and reliably orients the Rover and UAV for multiple orientations and landings of the bulkhead section of the vehicle.	In Progress
P.22	4.3.7.1	The Deployment system must restrict motion of the Rover and UAV in all directions until the deployment sequence is initiated.	Flight stability is dependent on all components in the payload bay remaining locked in place	All designs of the deployment system will be required to restrict motion of the Rover and UAV in the X, Y, and Z directions. All motion restricting designs will be extensively tested to verify proper functionality.	Complete
P.23	4.3.2	The target detection system must correctly identify the closest CFEA.	Minimize travel time and distance for the Rover.	The target detection software will be tested to consistently locate the closest CFEA during multiple simulations in which fluorescent material will be placed on multiple types of terrain. See Section 4.6.3 for system details.	In Progress
P.24	4.3.2	The target detection system must identify the corner of the CFEA that is furthest from the Rover.	Reduced risk of the Rover driving over the UAV	The target detection software will be tested to correctly and reliably identify the corner of the CFEA that is furthest from the Rover.	In Progress

Table 1: System Requirements and Verification Plan

## 4 Detailed project description

### 4.1 System theory of operation

The scoring payload this year is the Lunar Sample Retrieval System (LSRS). The LSRS consists of three interconnected systems: the Retention, Orientation, and Deployment (ROD) System, a UAV with target detection capabilities, and an eccentric-crank Rover capable of

retrieving Lunar Ice samples. The ROD system is responsible for securing the LSRS during flight and orienting the LSRS before deployment, and it interfaces with the sled and rail assembly used for vehicle integration. Four solenoids attached to the sled extend into the Rover body and UAV sled to secure the LSRS during flight. Upon successful recovery, the solenoids retract and enable the Rover to translate out of the payload bay and to the UAV in the UAV-sled behind it.

The UAV fitted with a target detection system will then search for and locate the nearest CFEA. Target detection is accomplished by transmitting a live video feed from the UAV to a ground station. Image processing is done on the ground station and commands are sent back to the UAV. Once a CFEA is located, the UAV will land in the corner furthest from the Rover and will transmit its coordinates to the Rover.

Upon receiving coordinates transmitted from the UAV, the Rover will begin to travel to the coordinates of the UAV. Once the Rover has translated to the CFEA, the sample retrieval system will initiate. An Archimedes screw will extend from the Rover body into the sample and collect a 10 mL sample of simulated lunar ice. After the sample has been collected, the Rover will translate 10 linear ft away from the CFEA and conclude the LSRS mission.

For increased detail on the full payload mechanical and integration design, please refer to the Notre Dame Rocketry Team Flight Readiness Review (FRR) report available on our website or the NDRT AIAA website. A diagram of the mission plan can be found below in Figure 1, as well as a comparison of the modeled render of the system design and a picture of the physical assembly (prior to electronics integration) in Figure 2.

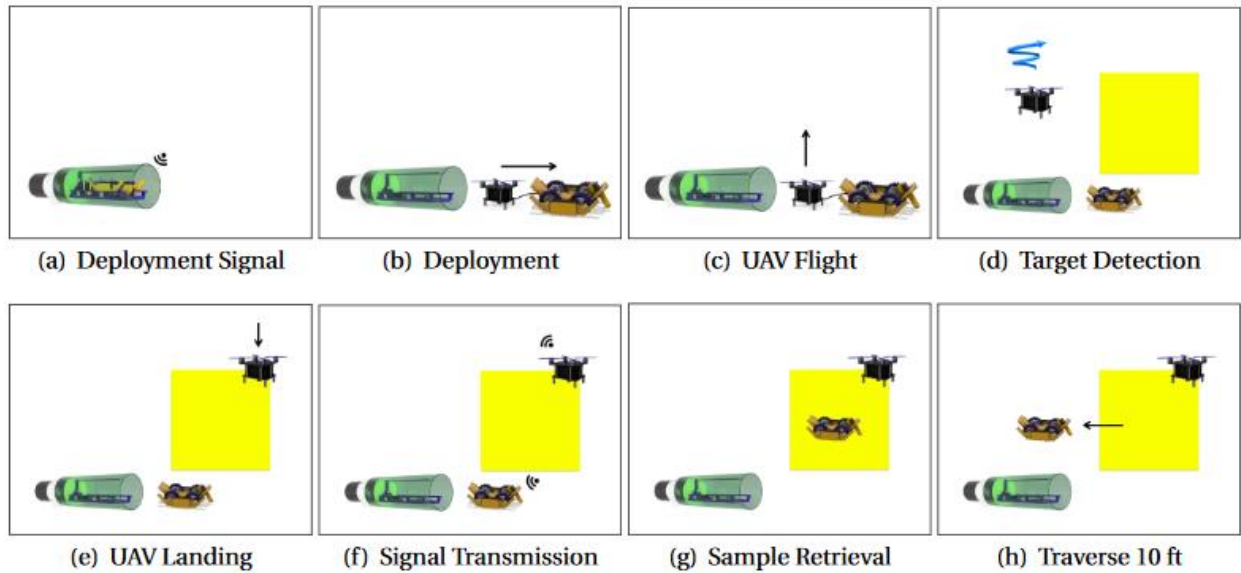


Figure 1: Breakdown of the payload mission actions.

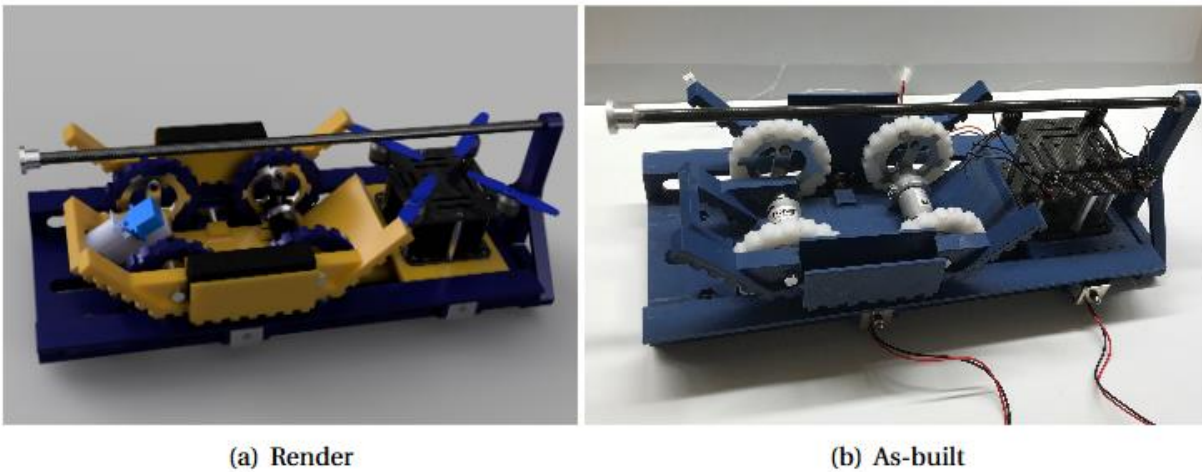


Figure 2: (a) Render of CAD model designed by NDRT in Fusion 360. (b) As built rover, UAV, and retention mechanical components.

The sample retrieval design was developed by the NDRT Payload team and consists of an archimedes screw which is powered by two servo motors, one which lowers the screw and one which drives its movement. Parts for the screw were 3D printed on campus, and the servo motors

are powered and controlled by our electrical system. The screw works by driving into the sample at a 20 degree angle of attack and then turning such that the sample is risen into the screw assembly. A slit in the upper section of the screw allows the sample to drop into a box affixed to the back of the screw and collect more than the 10mL required. The assembled screw and render of the rover with the screw are shown below in Figures 3 and 4.

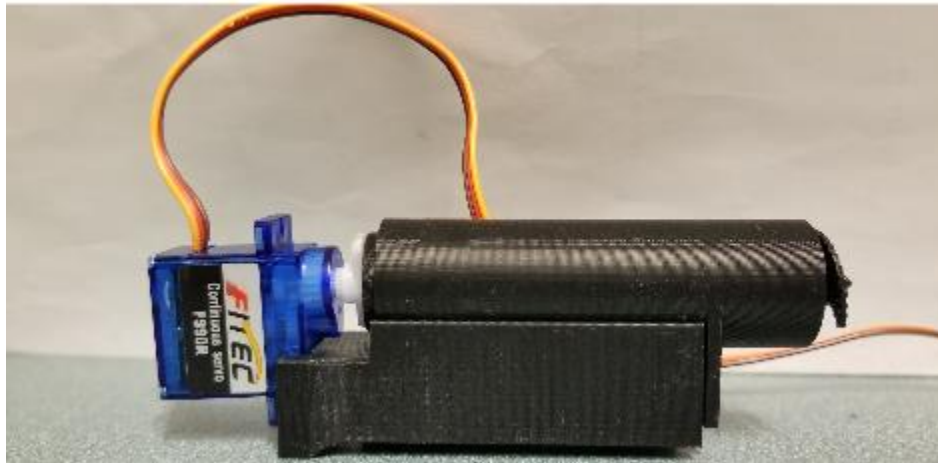


Figure 3: Assembled Archimedes screw for sample retrieval.

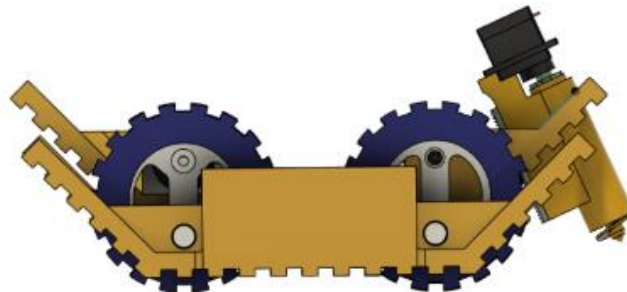


Figure 4: Rover design showcasing eccentric crank platform offset.

## 4.2 System Block diagram

**Overall system block diagram showing how it is divided into subsystems, and the interfaces between the subsystems.**

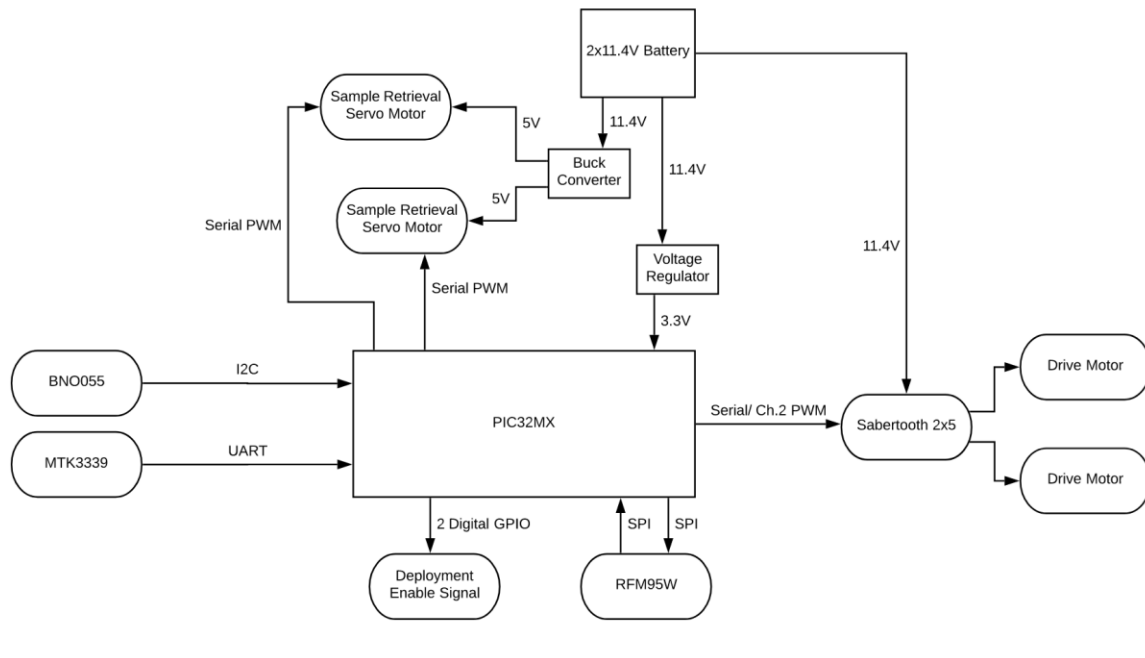


Figure 5: System Block Diagram

## 4.3 Subsystem Descriptions

### 4.3.1 Subsystem 1: Motor System

#### 4.3.1.1 Motor Overview

The Actobotics 98RPM Econ Gear Motor from Servo City was selected to provide actuation for the drivetrain of the rover. These motors were selected due to their small size and high torque of 524 oz-in at stall. The motor draws a mere 0.10 A at no load and 3.8 A at stall, which is lower than many competing options and provides flexibility in choosing from numerous available motor controllers meeting these specifications. Two motors will be used in total, one on

each side, and each motor weighs 0.20 pounds. The Econ Gear Motor is shown below in Figure 6.

The Sabertooth 2x5 Motor Controller was selected to control the drive motors for the rover. This controller can provide 5 amps of continuous current and 10 amps of peak current to two motor channels, which is enough to safely supply up to the 3.8A stall current of the drive motors without burning out the motor controller. The motor controller has a voltage rating of 6-18V, which exactly matches the accepted input range for the selected motor. This motor controller also provides flexibility in control methods, as the board can receive commands via either pulse width modulation (PWM) signals or a serial interface sending a set of bits identifying the speed at which to run each motor. The Sabertooth also incorporates circuit protections to avoid operation while overheating or drawing too much current. The Sabertooth can be seen below in Figure 6 below.



Figure 6: Actobotics 98 RPM Econ Gear Motor, Sabertooth 2x5 motor controller.

#### 4.3.1.2 Motor Testing

The drive motors were first tested by using a PWM signal from an arduino to test that the motors could spin both directions, stop, and spin at any speed up to 98 rpm. After getting this to work, we used PWM signals from the PIC to the sabertooth motor controller to spin both drive motors and demonstrate full motor functionality.

## 4.3.2 Subsystem 2: Power Management System

### 4.3.2.1 Power Overview

In order to appropriately size the batteries, voltage regulator, and buck converter, the power requirements for our system were calculated. The power consumption for each component is listed in table 2 below.

Device/State	Current Draw (mA)
PIC32MX	120
LM2596-3V	10
LM2596-5V	10
BNO055	12.3
MTK3339	20
RFM95W	12.1
2x Motors: half-stall	4000
<b>Total Current:</b>	<b>4184.4</b>

Table 2: Estimated Total Power Consumption

This is not the max power draw that could be experienced by the system because the half stall current for the drive motors was used, so it can be seen as more of an average power draw. The total energy available in the two batteries is 3600 mAh, so with an average current draw of 4184.4 mA the rover has an estimated run time of 51.6 minutes.

### 4.3.2.2 Power Testing

All of the batteries were shipped fully charged and tested by measuring the voltage with a multimeter. Proper functionality was also verified by successfully charging the batteries the Li-Po battery charger and discharging the batteries to power the motors, buck converter, and voltage regulator.

## 4.3.3 Subsystem 3: Sensor System

#### 4.3.3.1 Sensor Overview

The rover design implements a GPS module and an Inertial Measurement Unit (IMU) in order to enable autonomous control. This subsystem would interface with the microcontroller to provide the autonomous control function necessary information.

The GPS module is required to provide accurate and sensitive location information to the rover such that the rover can autonomously navigate to the sample retrieval area. The module must provide this location information at a rate which allows the rover to adjust its trajectory in a reasonable amount of time. To fulfill these requirements, the MTK3339 GPS module from GlobalTop Technology was selected. This module provides a built-in ceramic antenna for tracking from GPS satellites with automatic switching capability and a -165 dBm sensitivity to maintain connection. The 10 Hz refresh rate will be sufficient for the speed of the rover and the 70 mW power rating will allow for longer operation. The GPS module is shown below in Figure 7.

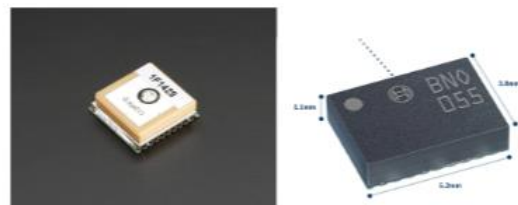


Figure 7: From left to right, MTK3339 GPS Module, BNO055 IMU

The IMU module is required to collect acceleration and magnetometer measurements. The acceleration data is required to measure if the rover is moving as well as detect orientation

prior to deployment. The magnetometer data is required to determine the compass orientation of the rover in order to correct the orientation and head in the direction of the UAV transmitted GPS coordinate. These measurements must be sufficiently accurate, sensitive, and robust such that the rover is able to reliably use the measurements for correct navigation. In addition, these measurements must be sampled and provided at a sufficient rate such that the rover can reliably use the data when necessary for autonomous control. To fulfill these requirements, the Bosch BNO055 IMU was selected. This package allows for multiple sensor measurements to be collected into a single component package over a single I2C interface to the PIC32. A strong benefit of this package is that it is designed to perform data fusion of the acceleration and magnetometer data, allowing it to provide tilt-compensated compass data. An external 32kHz oscillator will be used to provide more accurate performance from the BNO055. The BNO055 integrated circuit packaging is shown above in Figure 7.

#### 4.3.3.2 Sensor Testing

Only basic testing for these sensors was accomplished due to the interference of Coronavirus. The completed testing involved implementing Arduino libraries to successfully retrieve data from the IMU, and successfully receiving and interpreting GPS coordinates on the PIC32. We were in the process of transferring testing of the IMU over to PIC microcontrollers when our semester was disrupted. Planned testing that was not completed was to implement the necessary code on PIC kit boards to ensure that communication with the sensors could be achieved outside of using Arduino, then begin testing control algorithms for the autonomous control using the data received from the sensors.

#### 4.3.4 Subsystem 4: Communication System

#### 4.3.4.1 Communication Overview

The rover receives commands through a Hope RF RFM95W radio module. This module was chosen based on its long range (LoRa) module with a range of 1.25 miles, license-free ISM 915 MHz band operation, 100mW power rating in order to fulfill NASA Student Launch requirement 2.22.9, and SPI interfacing to the MCU. Communication is utilized for manual control, sending telemetry data back from the rover, sending destination coordinates to the rover, and sending the deployment signal to release retention on the rover. This is shown in Figure 8.

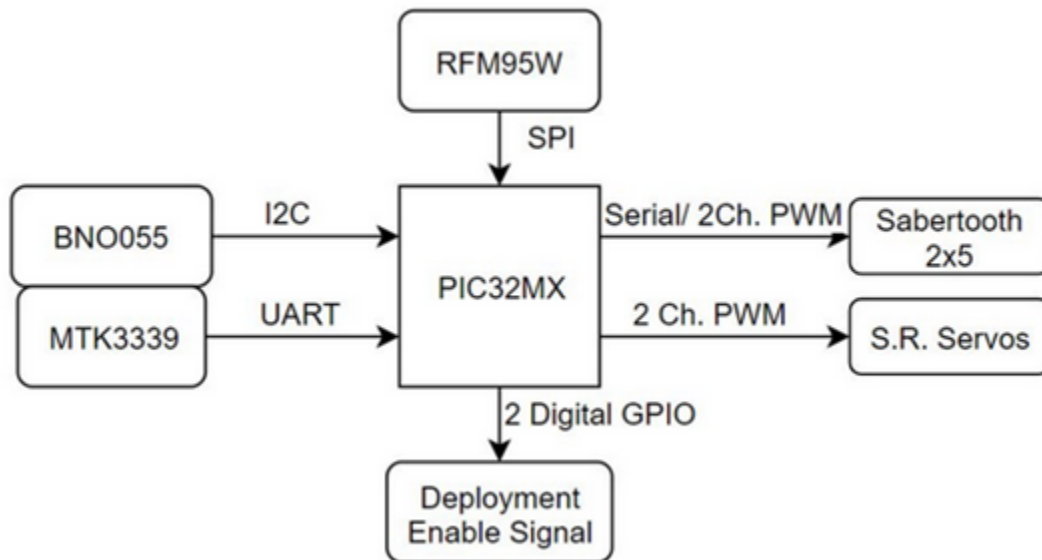


Figure 8 Communication protocol block diagram.

#### 4.3.4.2 Communication Testing

Communication was tested first as a proof-of-concept with an arduino. Commands were successfully sent to the Sabertooth Motor Controller, with speed, direction and stop commands sent, at around 650 m. This distance is greater than the expected payload travel distance of 300

m. Manual control, telemetry data, and the deployment signal tests were planned, but unfortunately were not conducted due to campus closing.

### 4.3.5 Subsystem 5: Microcontroller Intelligence System

#### 4.3.5.1 Microcontroller Overview

The microcontroller is required to provide the ports and serial communications necessary to interface with the other subsystems. The Microchip PIC32MX795F512H was selected as the MCU that will control the rover system. The PIC32 provides 6 UART modules, 4 SPI modules, 5 I2C modules, 5 pulse width modulation (PWM) pins, and a maximum of 53 GPIO pins. This provides ample pins for the rover system, which will utilize one I2C module, two UART modules, one SPI module, and four PWM signals. The PIC32MX will be configured using PICKIT3 programming modules available to the team through the Notre Dame Electrical Engineering design labs and programmed using Microchip's MPLAB X software. A block diagram of the interface protocols used with the PIC32 are shown in Figure 8 in Section 4.3.4.1.

The intelligence system of the microcontroller must be able to switch between autonomous and manual control of the rover. The microcontroller software must also remain idle until deployed and communication is received from the UAV or ground station. In autonomous mode, the microcontroller must use a control algorithm that successfully utilizes the data collected from the sensors and the GPS coordinates from the UAV to navigate to the sample collection area. In manual mode, the microcontroller must be able to convert commands received from the RF communication to proportional signals sent to the motors. The designed control plan for the rover is shown in Figure 9 below.

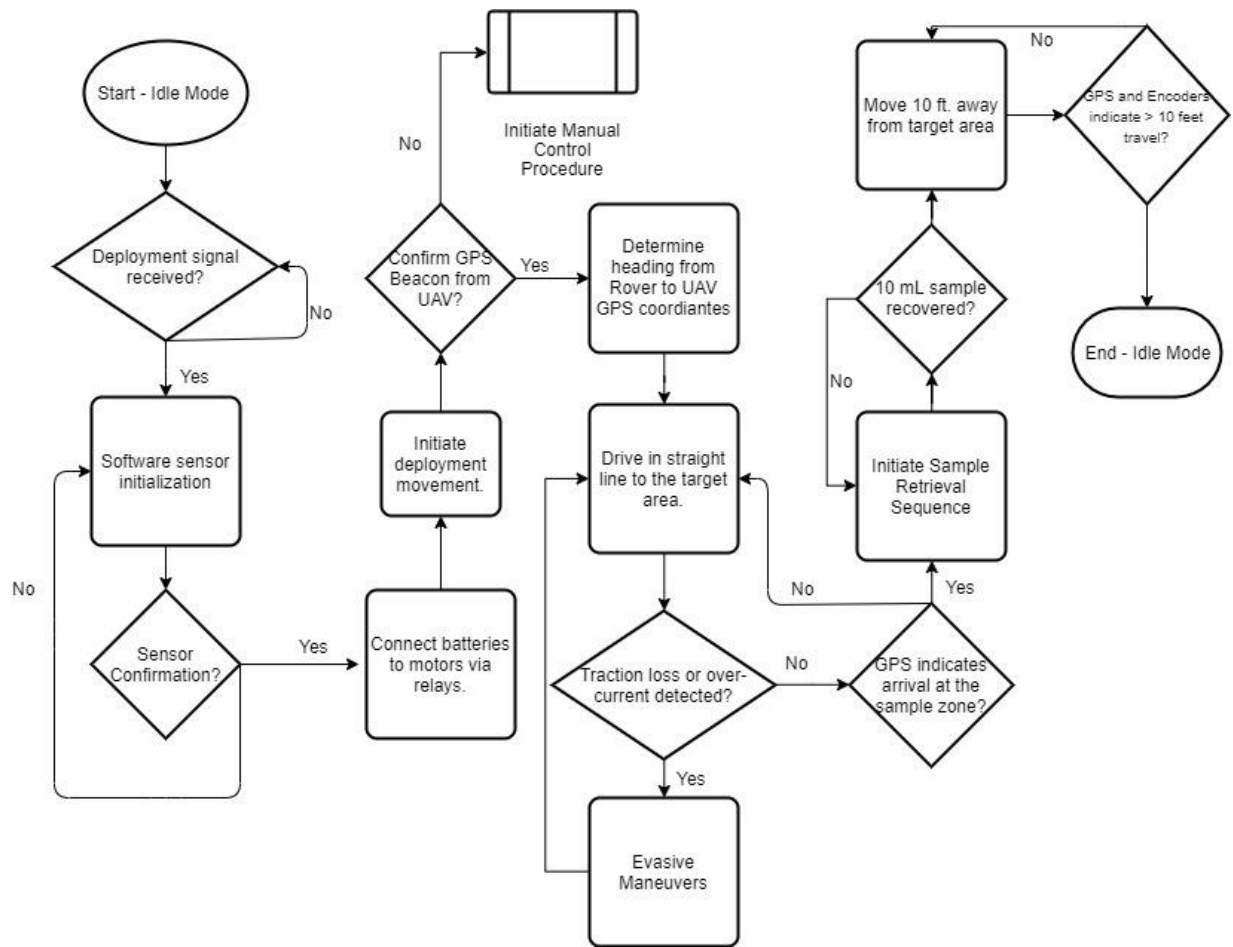


Figure 9: Rover Control Flow Diagram

In order to autonomously direct the rover using GPS data and compass heading, algorithms are needed to orient the rover. Using the GPS coordinates provided by the UAV and the ones recorded by the GPS module onboard the rover, the rover software will calculate the necessary bearing using the formula in the equation below:

$$\theta = \text{atan2}(\sin(\Delta\lambda) * \cos(\phi_2), \cos(\phi_1) * \sin(\phi_2) - \sin(\phi_1) * \cos(\phi_2) * \cos(\Delta\lambda))$$

Equation 1: Heading calculation from GPS coordinates.

Where  $\phi_1, \lambda_1$  is the start point,  $\phi_2, \lambda_2$  the end point, and  $\Delta\lambda$  is the difference in longitude.

The on board BNO055 inertial measurement unit will be used to calculate the current

heading of the rover. The BNO055 shall be configured and calibrated in the COMPASS mode as outlined in section 3.3 of its datasheet. This will allow the BNO055 to fuse data from the magnetometer and accelerometer to provide tilt compensated compass data for calculating heading by taking the inverse tangent of the X and Y components of the magnetometer data.

#### 4.3.5.2 Microcontroller Testing

Once the complete board was assembled, testing could take place. Obviously the first test done was making sure all the power LEDs lit up, and all of the power voltages were correct. The only issue found was bridged solder joint connecting power and ground on the underside of the LoRa unit that was not visible from just looking at the board. No components were damaged though, as initial testing was done with a bench top PSU that was intentionally current limited to 100mA. After the bridged joint was tracked down, all power voltages checked out and the power LEDs lit up. The final initial testing was to connect the Pickit and make sure that the microcontroller was recognized correctly, and that a program could be successfully downloaded to the board.

After this initial testing was completed the easiest testing to be done was with the GPS module. LEDs were installed that indicated if the unit was on and functioning properly and if the module had a successful GPS lock. Additionally, small testing pads were included on the board so that a logic analyzer could be easily connected to the UART transmit and receive lines between the GPS unit and the PIC32. A simple test code to make sure that the GPS unit and PIC was written to ensure that the GPS was communicating properly and that meaningful data was being sent.

The next easiest thing to test was the radio communication between another LoRa radio module and the one connected on our board. This was fairly easy to test too. There was a separate radio module connected to an off board arduino so we could easily see in the serial window, communication between what our board and that unit. Test code was written and wireless communication in which our board sent data and was received on another LoRa was seen to work. To test received communication, test code was written so that a simple PWM signal was sent to a small servo motor when a command was received by the off board LoRa.

Sub-system and circuit validation testing was not done to the IMU or the crystal serving as its external clock. We had not had the need for that particular subsystem to be working before the Coronavirus pandemic, and so no code was written to test the functionality of that part of the board, however, in the second round of boards we ordered, pads were added so testing the clock and data lines would be relatively trivial because a logic analyzer could be easily connected, and simple code could have been written to ensure proper circuit functionality

The last little bit of testing was to make sure that the proper PWM and sabertooth board signals made it to the edge of the board. This was done with a combination of the logic analyzer and simply hooking up the sabertooth board and motors as well as the small servo motors we were planning on using for sample retrieval.

The proposed software algorithm and manual control were unable to be tested due to the disruption of the semester. Planned testing of the control algorithm would be to send the rover GPS coordinates of a location on campus and observe if the rover can successfully navigate to the coordinates. Testing of the control algorithm would also involve communication from the rover to the testing ground station to have a detailed log of what functions, interrupts, and control decisions were being made by the microcontroller. Planned manual control system testing was

observation and verification of the signals being sent to motors by the microcontroller due to signals received from the RF communication.

### 4.3.6 Subsystem 6: Retention System

#### 4.3.6.1 Retention Requirements

Retention of the LSRS during flight is achieved using four solenoids that are epoxied into the sliding platform. The sliding platform itself is then secured to the rail platform by two lock-nuts and bolts in the fore section of the platform. The two solenoids in the fore section of the platform slide into pin-holes in the Rover body and secure the Rover during flight. Motion of the Rover links is restricted by the nature of the eccentric crank mechanism design. The two solenoids in the aft section of the platform slide into pin-holes in the UAV-Sled. The UAV rests on the UAV-Sled by threading the UAV landing struts through four holes on the UAV-Sled. The two landing struts in the aft side of the sled have through holes which allow two epoxied pins in the aft section of the sliding platform to freely slide into the struts and securely hold the UAV in the UAV-Sled during flight.

The sliding platform serves as a housing for the LSRS and the retention components. The team purchased four Adafruit Medium Push-Pull solenoids as discussed in CDR. The four solenoids are placed in the respective slots of the sliding platform as well as the two UAV retaining pins. While all four solenoids are press-fit into the housing slots, 5-minute epoxy was used to ensure that the solenoids are secured during flight. The retaining pins were manufactured out of a 1/4 in. Aluminum 6061 rod using a Manual Lathe in the Student Fabrication Lab and were attached to the sliding sled using RocketPoxy. The UAV-Sled was 3-D printed on a Statasys F107 at the Notre Dame Idea Center and the sled was printed using ASA filament. The retention platform is shown below in Figure 10 with the solenoids installed.



Figure 10: Retention platform assembled.

The retention electronics consists of an Adafruit Itsy Bitsy controller which will receive the trigger signal from the rover controller to actuate the solenoids and allow the rover and uav to exit the launch vehicle. The solenoids are powered by a small 7.4V LiPo battery with power delivered to the solenoids through a MOSFET transistor, which is sufficient given the short operating time. The MOSFET gates are controlled by the Adafruit controller and act as a switch to deliver power to the solenoids. Additionally, a diode across each solenoid provides a circuit for transient current to dissipate following the solenoids turning off to avoid damage to the solenoids. The solenoids are connected via a 3pin rectangular moxex connector. The PCB for the retention electronics is shown below in Figure 11. The schematic can be found in the appendix, Figure 24.

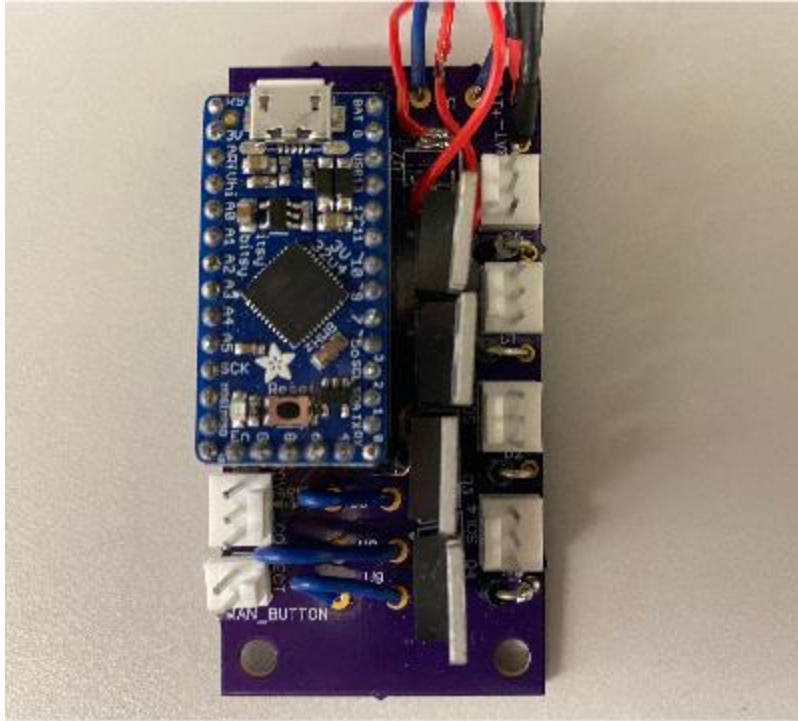


Figure 11: Retention Board Assembled.

#### 4.3.6.2 Retention Testing

During a full scale flight test on February 23, 2020, the payload system was loaded into the rocket's payload bay for retention testing of the solenoid strength. Due to component delivery and assembly delays due in part to the Coronavirus situation, this test did not feature active electronics but rather served to demonstrate the strength of the solenoids to retain the payload vehicles. This test served to partially fulfill requirement P.22 stating that the ROD system would restrict motion until a deployment signal from the ground station. Additionally this test served to demonstrate the free rotation orientation design of the system, allowing the system to orient upright following the nose cone ejection at 400 feet.

Following a successful recovery, the payload bay was found to have successfully retained and oriented demonstrating the strength of the solenoid system and low-friction free body orientation design. The recovery is shown below. Further planned testing involves electronics

integration testing to verify solenoid retraction and payload deployment following a command from the ground station. Due to the extenuating circumstances this testing was postponed and not completed at this time since we have not been able to return to campus for testing.



Figure 12: Payload system upon successful recovery and demonstration of orientation and retention system strength.

## 4.4 Interfaces

### 4.4.1 Board Schematics and Board Design

Shown below are the board schematics for each of the individual subsystems of our board. The recommended circuit implementation was used from each datasheet from each of the major components we used, namely the IMU, the LoRa radio, the GPS module, and the Pic32.

There was no deviation from the recommended circuit implementation that was found in the datasheets. We saw no need or merit in reinventing the wheel so to speak.

As for the actual physical implementation on the board, recommended layout guidelines were also followed. Important power supply capacitors were placed as near their proper power and ground pins as possible. The noisy switching power supply for the 5 volt power for the servos was placed far away from any of the sensitive sensor and Pic communication lines. A simple 3.3V linear regulator was employed to power the rest of the sensors so that clean power could be confidently supplied.

Both high frequency antenna connections on the board were given wide berths on all sides by any copper flood so that any potential and harmful parasitic capacitance was avoided. Other than those considerations, on the board generally copper traces running on the bottom plane ran horizontally, while traces on the upper plane ran vertically, but this was not a hard and fast convention for this particular board design. Seen below in Figures 13, 14, 15, 16, 17, 18 are the schematics of each of the individual sensors and subsystem components as well as a full shot of the board design.



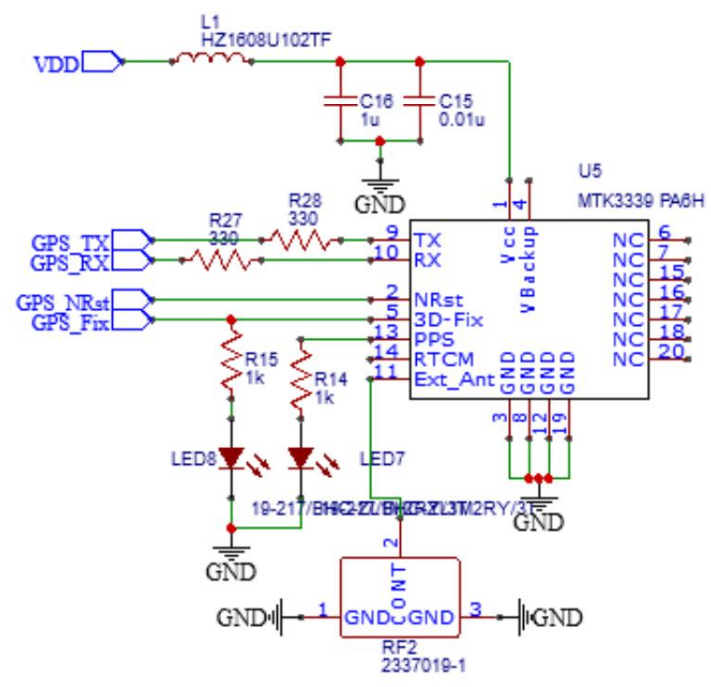


Figure 14: GPS Module

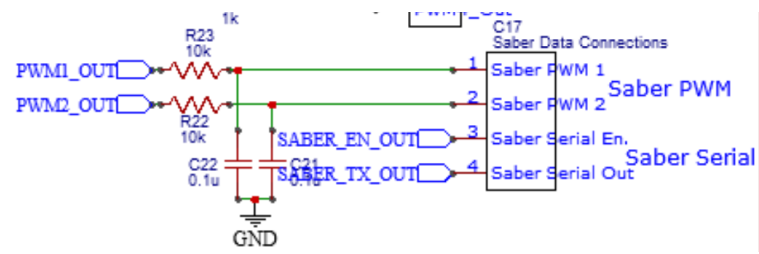


Figure 15: Saber 2x5 MC PWM Connections

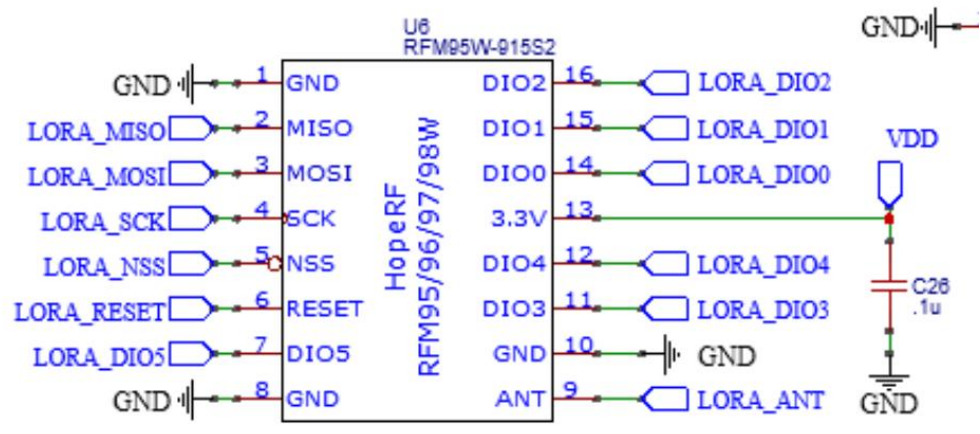


Figure 16: LoRa Radio Module

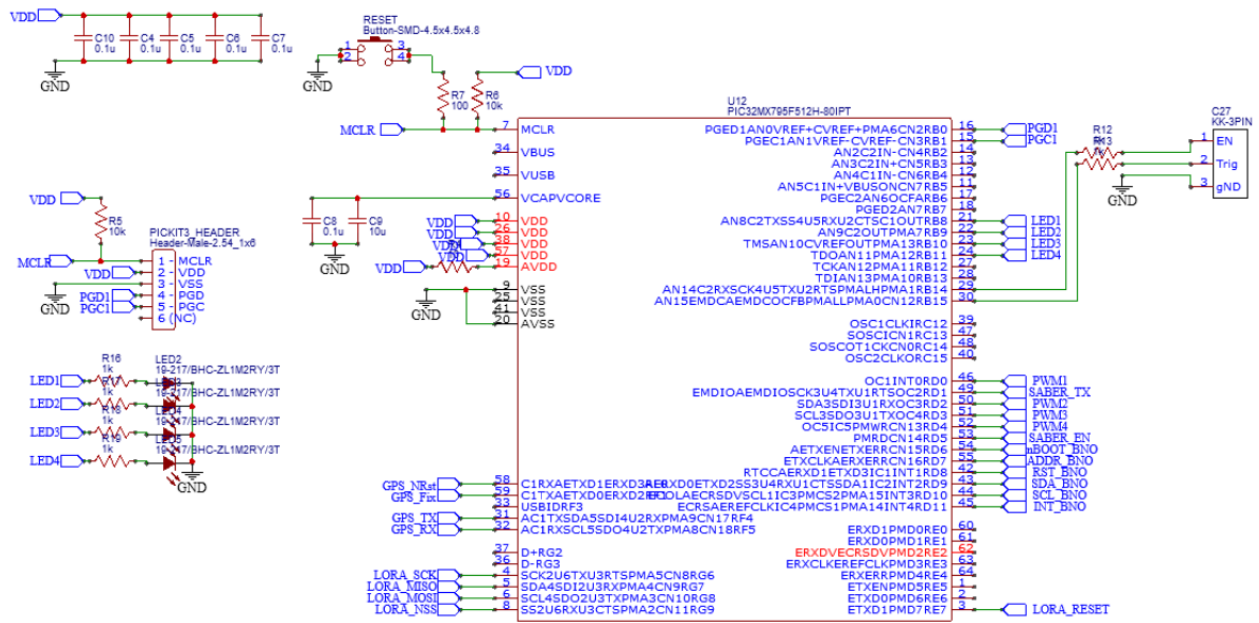


Figure 17: PIC32 Module

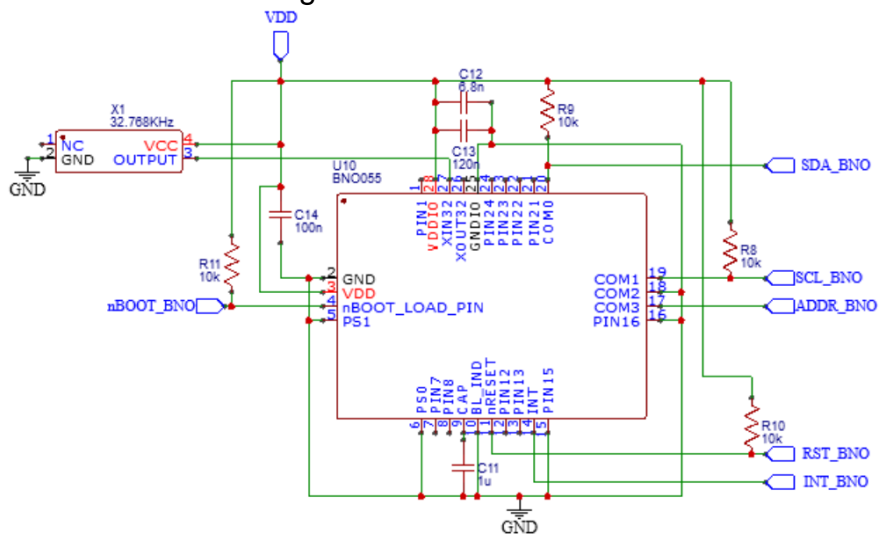


Figure 18: IMU Module

# 5 System Integration Testing

## 5.1 Subsystem Testing:

The subsystems were developed individually. The motors were interfaced with the Sabertooth, and test commands were sent from an arduino using PWM. The motors were

successfully operated. The power management subsystem was tested by the discharge time and max current output. They complied with the 4.18 A max current limit and the estimated run time of 51.6 minutes.

The GPS module was tested by connecting to the PIC32, and the location data was received by the PIC32. The GPS was functional in the connection to the PIC32.

The IMU was tested by connecting to an arduino test board, and the output was read through sample software provided by Bosch. The integration of the Sensors was not accomplished, as Coronavirus shut down campus. It is assumed that if all of the subsystems were tested individually, that they would integrate. The assembled board can be seen below in Figure 19.

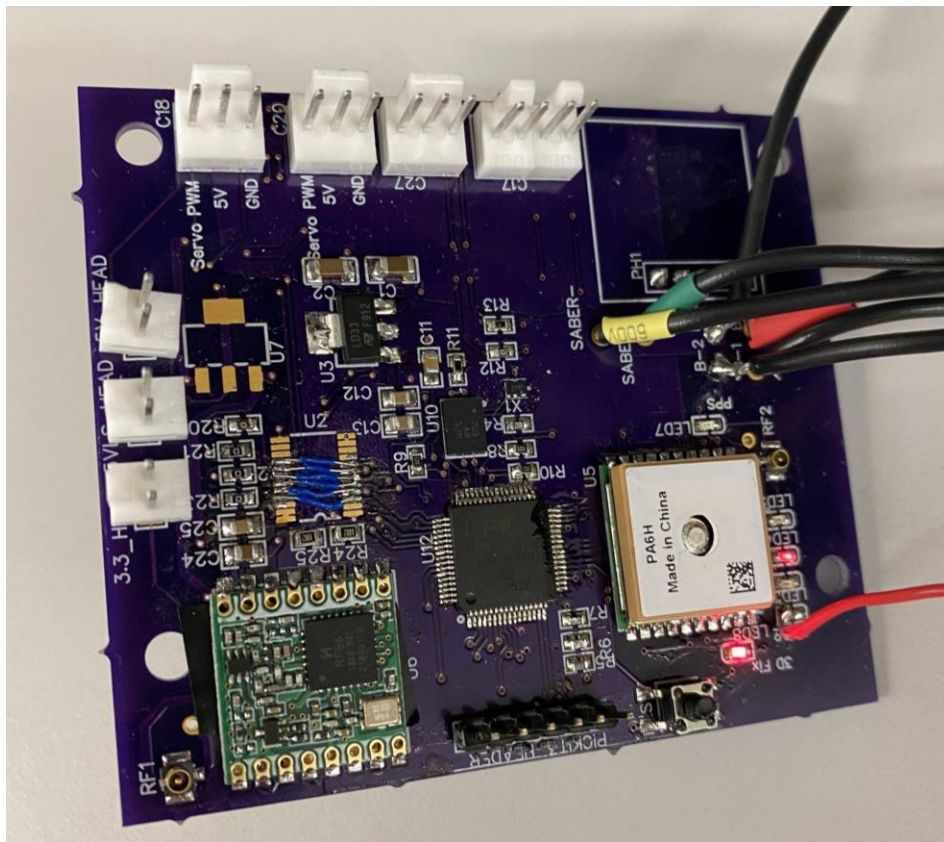


Figure 19: Assembled rover board undergoing subsystem testing.

## **6 Installation manual**

### **6.1 How to install your product**

The Solenoids will be properly inserted into the slots on the sliding platform. The UAV sled with the UAV and the Rover will be placed into position on the platform and the solenoids will be inserted into the respective slots. The sliding platform will then be slid onto the stationary platform and be secured using the nuts and bolts. The Rover, UAV, and ROD systems will be connected to their respective batteries. The Ground station will be powered on and communication established with each system. The manual controller will function through the ground station developed with NDRT and have assigned buttons for driving each of the motors forward or backwards.

## **7 To-Market Design Changes**

This product was not designed to be a consumer product because it was made for the NASA student launch competition with a very specific set of requirements. There is also the issue that the build and launch were not completed because of the Coronavirus so there may have been issues with the design that remain unrealized. However, with that being said there are some things that would need to be changed or updated if this were to become a marketable product.

One thing that would need to be more developed would be the autonomous control system for navigating to the payload site. While successful motor control was demonstrated, we were not able to get to programming the logic of the rover to use the GPS coordinates and data

from the IMU to navigate to the rover. In order to do this, we would need to establish communication from our PIC to the GPS and IMU, and create a control algorithm to use the data in order to determine the necessary motor outputs to steer the rover to the payload site.

Another concern for bringing this product to market would be securing licenses for customers to legally broadcast in the 2.4Ghz frequency band. In order for us to use radio communication it was necessary for one of our group members to attain an amateur radio license to operate the communication with the UAV. The 915Mhz band that the rover uses to communicate with the ground station does not require a license. If this was sold as a consumer product, different radio bands may also need to be used depending on FCC requirements which could change the hardware needed for our RF system to work. Finally, there also would be a concern with radio interference from other people that could either accidentally or purposefully take control of the system rover or UAV by communicating in our same frequency band. We would need to add security measures and make a custom communication protocol that would not be vulnerable to radio interference.

If this were to be sold commercially, we would need to add some redundancy measures. Both the UAV and the Rover each only have one microcontroller while many flight control systems have 3 flight control computers. We would probably add a redundant microcontroller to the rover in case the first one failed or was failed in flight. Redundant GPS, IMU, and RF sensors would also be a good idea to include because a sensor could be damaged or disconnected during flight.

Another addition that could make this product more marketable would be adding a camera that could be used to livestream video feed from the rover to the operator. Most rovers

have this functionality because rovers are often sent places humans cannot reach and the user will want to be able to see what is going on around the rover. This was something that was considered as a stretch goal for our design because we had access to a camera but we did not have time to get to it because of the time constraints.

## 8 Conclusions

Ultimately, the difficulties created by the COVID-19 pandemic make it difficult to access the success of the project in achieving its original end goal. From the month long delay in the supply chain to receive our boards in January to the closing of campus, the coronavirus situation impacted our project immensely, but it is our strong belief that had we returned to campus we would have been able to achieve our mission plan, as we were progressing into final build and integration testing. Our team was successful in designing a robust electrical system and performing subsystem testing despite these setbacks, and worked well with the Notre Dame Rocketry Team to plan integration onto the rover and assisted in the electrical design of other systems such as the retention system which we adapted into our design and in providing safety oversight for the Air Braking System and Recovery electronics. The design showcased a spectrum of things we have learned throughout our education, including plenty of embedded systems applications with programming for UART, I2C, SPI, PWM etc., as well as applying our learning in power delivery and radio communications to control the system.

While the pandemic was one of the greatest obstacles in our senior design project, it also offered some of the most significant professional growth opportunities. Our supply chain issues receiving parts from China during the emergence of the pandemic there in January provided real-

world experience with supply chain management that will be pivotal to our success as engineers in our respective industries. This experience has taught us the importance of contingency planning around a critical path of mission objectives and the value of getting ahead of schedule to mitigate the impact of unpredictable delays and situational transitions such as moving to remote learning. We learned to work well with our fellow cross-disciplinary engineers on NDRT and mutually deal with setbacks by both of our sub-teams.

If we were to go forward with new modifications to the system design, our primary focus would be on finishing the development plans we had for the second half of the semester. This means finishing component integration testing and programming, rover integration testing, and full scale mission testing. With additional time, improved user experience would be a focus on providing more meaningful data to the manual and autonomous controller for interpretation, and improved control system modeling for the system to respond to unknown terrain. In the context of the competition, this project provided a great learning experience towards an end goal for the system of being able to recover a sample, and perhaps in the future develop towards a system doing analysis of the sample all on board the rover.

## **9 Appendices**



Figure 20: NDRT 2019-2020 competition vehicle during a February 2020 test launch.

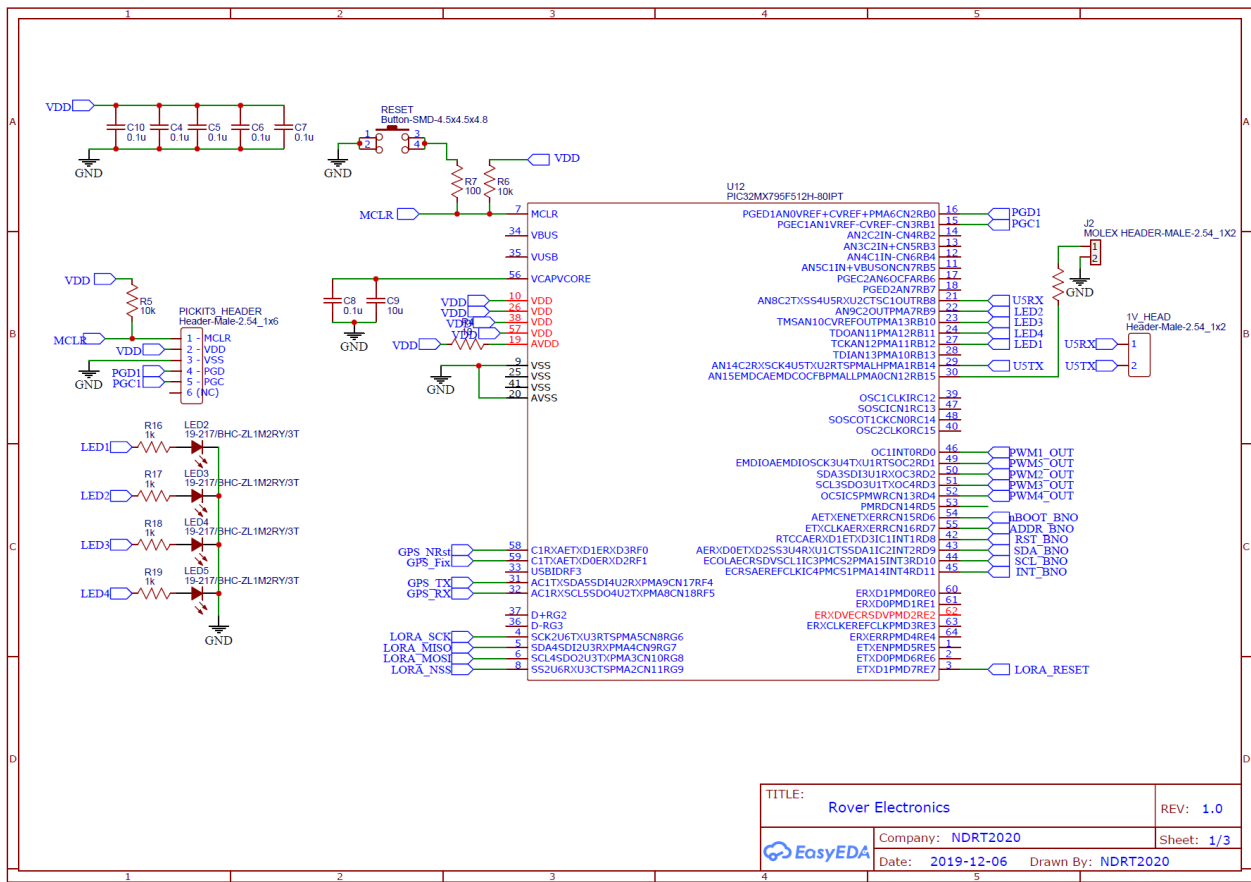


Figure 21: Rover electronics schematic, PIC32.

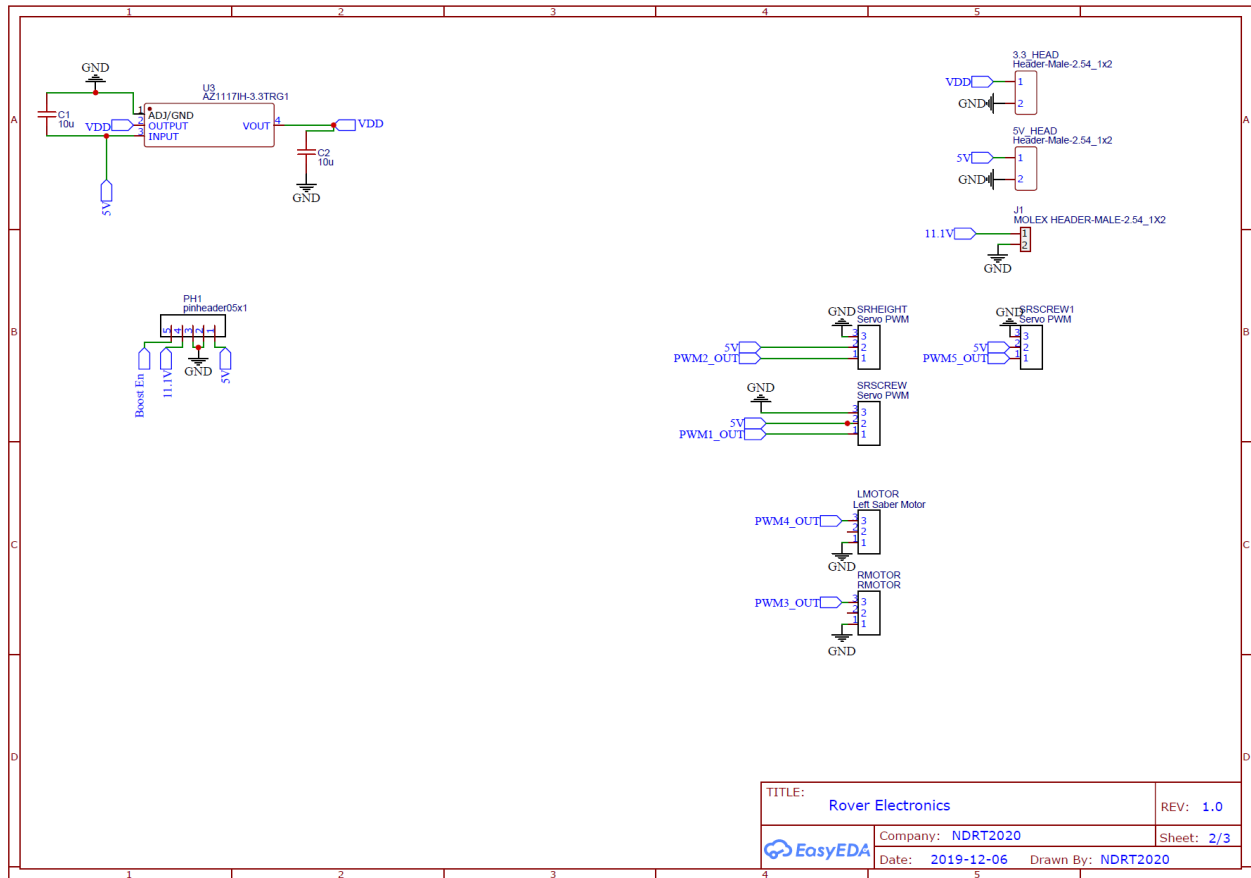


Figure 22: Rover electronics pinouts and linear regulator.

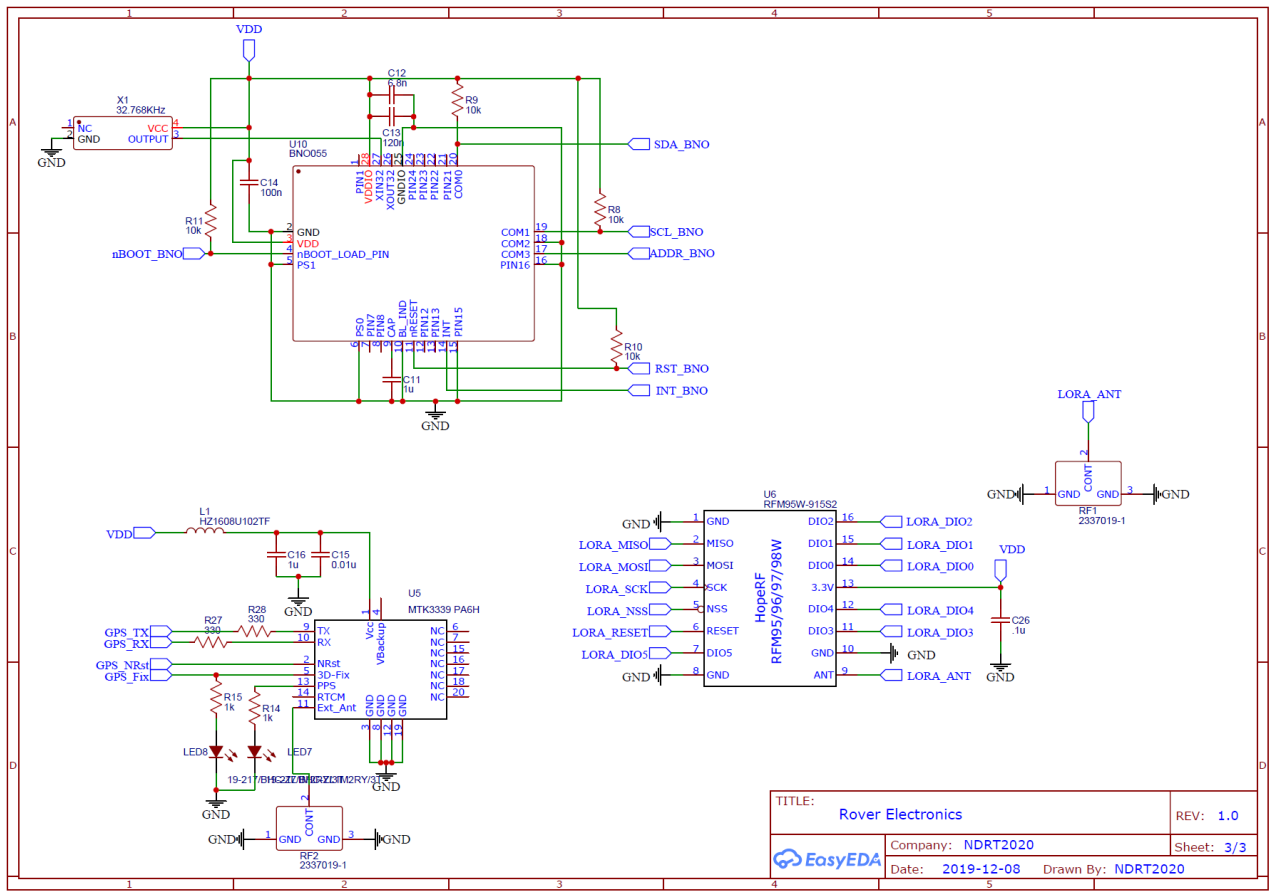


Figure 23: Rover electronics sensor schematic.

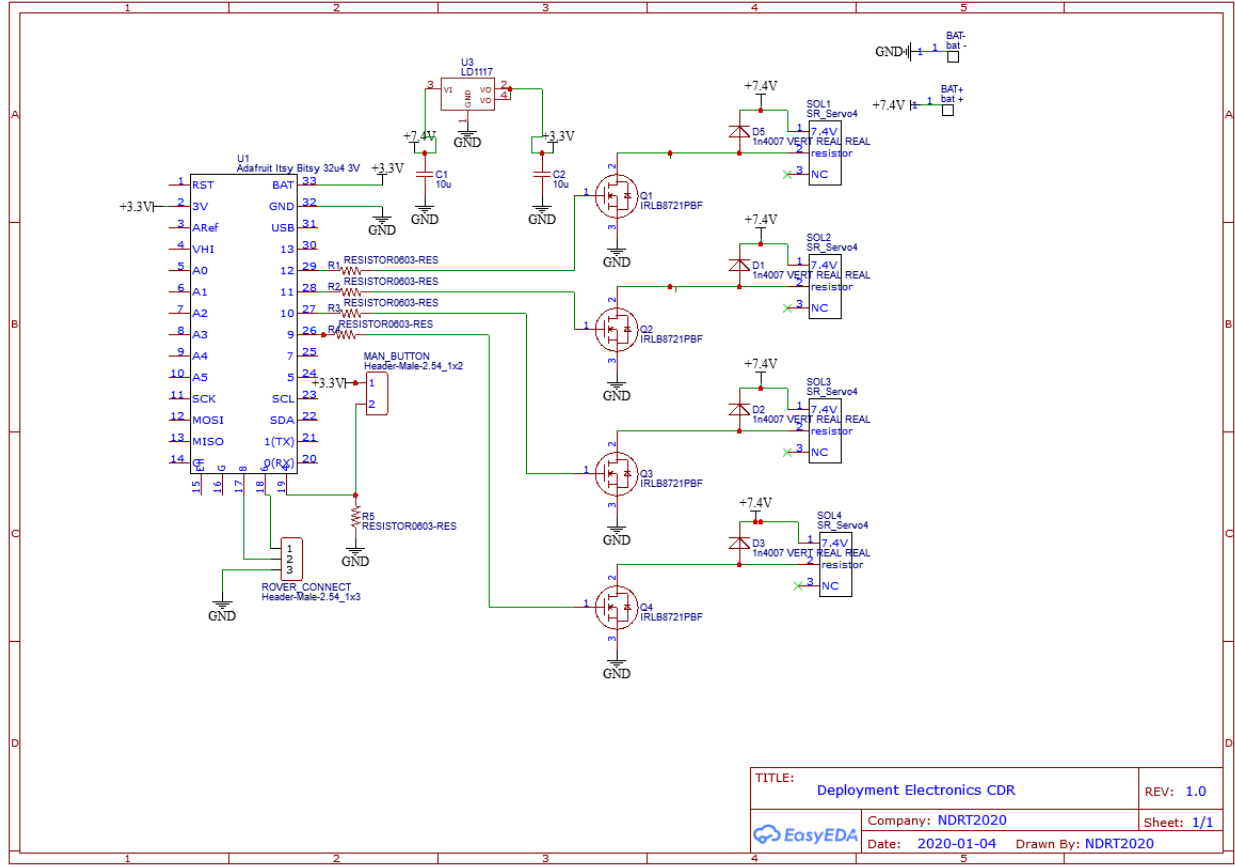


Figure 24: Retention board schematic.

**Budget**

Item	Vendor	Description	Qty	Price Per Unit	Total Cost
Level Shifter	Digikey	296-18593-1-ND	2	\$1.050	\$2.10
Integrated Circuit	Digikey	PIC32MX795F512H-80I/PT-ND	1	\$8.750	\$8.75
5V Voltage Regulator	Digikey	LM2596S-5.0/NOPB-ND	1	\$5.720	\$5.72
3.3V Voltage Regulator	Digikey	LM2596SX-3.3/NOPBCT-ND	1	\$4.910	\$4.91

3.3 V, .5 A Voltage Regulator	Digikey	296-17616-1-ND	2	\$0.61	\$1.22
IMU	Digikey	828-1058-1-ND	1	\$11.160	\$11.16
GPS	Adafruit	MTK3339 PA6H	1	\$29.950	\$29.95
Motor Controller	Robotshop	Sabertooth Dual 5A R/C 6-18V	1	\$57.950	\$57.95
Li-ion Batteries	HobbyTown	ProTek RC 3S 90C 1800mAh	3	\$38.930	\$116.79
5V 2.5A Buck Converter	Pololu	D24V25F5	1	\$10.950	\$10.95
RF Transceiver Module	Digikey	RFM95W-915S2-ND	2	\$13.570	\$27.14
RF Transceiver Connector	Digikey	A144746CT-ND	3	\$0.210	\$0.63
Reset Button	Digikey	PTS647SN50S MTR2LFSC-ND	2	\$0.140	\$0.280
Oscillator	Digikey	1473-30151-1-ND	1	\$1.210	\$1.210
330 ohm 0603 Resistor	Digikey	RMCF0603JT3 30RCT-ND	10	\$0.014	\$0.140
10 ohm 0603 resistor	Digikey	311-10.0HRCT-ND	10	\$0.046	\$0.460
6.8nF 0805 Ceramic Cap	Digikey	399-1157-1-ND	3	\$0.120	\$0.360
120nF 0805 Ceramic Cap	Digikey	311-4323-1-ND	3	\$0.180	\$0.540
Ferrite Bead	Digikey	732-4484-1-ND	2	\$0.170	\$0.340
OSH PARK	OSH PARK	Full Order	1	\$139.900	\$139.900
OSH STENCILS	OSH STENCILS	Full Order	1	\$23.900	\$23.900
JLCPCB	JLCPCB	Coronavirus Delays (literally)	1	\$54.450	\$54.450
rework wire	Digikey	1528-2005-ND	1	\$7.500	\$7.50

Power Resistors	Digikey	P0.75W-1BK-ND	4	\$0.270	\$1.08
3.3 regulator	Digikey	AP2114HA-3.3TRG1DICT-ND	5	\$0.360	\$1.80
5 volt regulator	Digikey	497-11659-1-ND	1	\$1.020	\$1.02
<b>Total:</b>	<b>\$510.25</b>				

### Complete Software listings

All code for this project can be found in the public GitHub repository found at this link.

<https://github.com/hbrown6/roverPIC>

### Relevant parts or component data sheets

#### GPS Data Sheet

<https://cdn-shop.adafruit.com/datasheets/GlobalTop-FGPMMPA6C-Datasheet-V0A-Preliminary.pdf>

#### IMU Data Sheet

[https://cdn-shop.adafruit.com/datasheets/BST\\_BNO055\\_DS000\\_12.pdf](https://cdn-shop.adafruit.com/datasheets/BST_BNO055_DS000_12.pdf)

#### RF Data Sheet

[https://cdn.sparkfun.com/assets/learn\\_tutorials/8/0/4/RFM95\\_96\\_97\\_98W.pdf](https://cdn.sparkfun.com/assets/learn_tutorials/8/0/4/RFM95_96_97_98W.pdf)

#### Sabertooth Data Sheet

<https://www.dimensionengineering.com/datasheets/Sabertooth2x5.pdf>

Pololu 5V, 5A Step-Down Voltage Regulator D24V50F5

<https://www.pololu.com/product/2851>