

# **LUNAR-CONNECT**

## **Lunar Unmanned Network for Advanced Robotic Collaborative Observation Navigation Networking and Exploration with Continuous Transmission**

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## 1 EXECUTIVE SUMMARY

Lunar exploration is undergoing rapid changes and growth, driven by scientific curiosity and the vision of establishing a sustainable human presence in space. A combination of technological innovations has allowed us to get to where we are, and the rapid growth of this industry creates the need for new technologies and the design of new and improved exploration rovers. Our senior design project focuses on creating a mesh network of rovers to enable efficient communication on the Moon.

The project will improve the existing rover designed and built by Florida Space Institute. There are many alterations that will be made by our group. This includes an increase in power supply, a new PCB design, a camera, an antenna for communications, and many other features.

Since there is a high workload to make this project work, we will collaborate with another senior design group to guarantee the achievement of all our goals. Another team from UCF will be designing and building the communication tower for our team.

This project will be sponsored by the Florida Space Institute. Mike Conroy is a Project Manager with over 35 years of experience with Space System Design, Development, Maintenance and Operations experience with NASA (National Aeronautics and Space Administration) Projects, Programs, and Initiatives. He will serve as a mentor as well as a representative of FSI.

This document contains information about the project's research process, design process, testing, fabrication, budgeting, and others. The document will start with some context by elaborating on similar or related projects in the past. Then it will go over some of the relevant technologies studied to make an educated selection of core components.

## 2 PROJECT DESCRIPTION

### 2.1 PROJECT BACKGROUND AND MOTIVATION

Lunar exploration requires contributions from many teams from multiple different institutions. By developing a system of rovers, this project will make significant contributions to the future of Moon exploration.

There are many benefits that come along with creating a mesh network of rovers. One of them is that the operators will be allowed to avoid certain areas according to whether there is already another rover located there. This can improve safety and avoid collision as the operators will have data on rovers' locations along with live feed camera footage. Another benefit is the optimization of exploration strategies by avoiding redundant data collection. By gathering data of each of the rovers' locations, engineers will be able to conduct analysis on the areas that have and have not been explored by each rover, enabling better strategies when exploring new areas as well as returning to previously explored areas. Another benefit is efficient task tracking. By looking at the rovers' path and location, engineers can better understand how tasks were conducted and the most efficient exploration paths for each task. This technology also takes a step towards autonomy since the camera footage can be eventually fed into an autonomous program for collision avoidance or even self-driving.

This project is primarily intended to open the possibility for rovers to receive each other's location as well as sharing their own, creating a mesh network of rovers. Components will be added to facilitate the exchange of data such as a microcontroller unit with an antenna that sends signals to a communication tower. As proof of concept, the rover mesh network will deploy a file sharing system that will allow for future development of a location sharing system that unfortunately falls outside of the scope of the Senior Design context.

The project also includes doubling the power supply so that the rover can go longer distances for a longer period of time. This will enable the rover to explore wider sites as well as be more resistant to environmental obstacles such as hills, which require much more energy than a flat surface.

The project will also include a camera, which will facilitate the driving experience for operators. This data can also be used to visually evaluate sites in real time. Another possible use of this technology is if one of the rovers has a malfunction. A second rover can use that rover's location to find it and provide live footage of the malfunctioning rover, which can help operators diagnose the issue. This data can also be used for public engagement since the footage of the rovers on the Moon can be great content for outreach.

## 2.2 PROJECT GOALS AND OBJECTIVES

The overall goals for this project are:

- ☐ Convert the existing electrical components in the rover to handle double the existing power.
- ☐ Implement a system that allows for communication between rovers.
- ☐ Transmit video display from the rover to a mobile application.

The goals can be reached with the following objectives:

- Our project must have a mesh network, which is designed and implemented for a reliable and fault-tolerant mesh network architecture for lunar rovers, enabling continuous communication even in challenging lunar environments.
- Our project must focus on optimizing data transmission within the mesh network to ensure real-time data exchange and timely decision-making during lunar missions.
- Our project will be scalable in terms of any number of rovers can be able to communicate with each other.
- Our project will have double the power of the existing PSU and modifications to the existing electrical system to handle this input, allowing for the rover to travel longer distances and be more resistant to environmental circumstances such as hills and valleys.
- Our project will rework a wireless mobile application that enables remote operation of the rover's motor controls with an implementation of a clear and smooth live video feed display of the rover's frontal field of view.

There are two stretch goals for this project.

- One stretch goal is to have wireless charging through the use of supercapacitors. This will enable the rover to be charged by simply driving to the middle of the charging platform, with no need for human contact when charging.
- Another stretch goal would be to have the charging plug set up so that the rover can be guided by rails to the port and be charged remotely.



These two objectives will be considered stretch goals since they are not required to meet the main goals and they will require additional research and resources to carry out.

## 2.3 PAST SIMILAR/RELATED PROJECTS

The following projects are from previous UCF Senior Design teams and other related projects from other institutions that involve similar project goals or products that relate to the goals and objectives outlined in this project.

### 2.3.1 REGOLITH ADVANCED SURFACE SYSTEMS OPERATIONAL ROBOT SHOULDER (RE-RASSOR SHOULDER) (FLORIDA POLYTECHNIC CAPSTONE)

Given that the project being developed in this document is highly inspired by and builds off the RE-RASSOR rover project, it is beneficial to know what kinds of goals and objectives that other projects that build off the RE-RASSOR rover did and what setbacks were encountered. The RE-RASSOR Shoulder project involves the development of a rover designed to pick up and carry a payload of up to 25 pounds or 11 kilograms. The project is built on top of the RE-RASSOR rover project which designs the rover that the shoulder project works with. The objectives of the project were to: create the assembly strictly out of 3D printed materials using an FDM 3D printer and consumer-accessible components; enable the rover to carry an 11-kilogram object at the end of its 0.3-meter boom arm; and develop a mobile application to remotely control the movement of the rover as a whole unit and its boom arm. With respect to the software development, the application was required to be scalable and able to be modified in a way that allows for interfacing of multiple devices. The components used in the RE-RASSOR shoulder project consist of a Raspberry Pi, LM2596 Buck converter, a 12V, 9Ah battery, 100 capacitor, Arduino MEGA 2560, a RAMPS 1.4 motor driver shield, A4988 motor driver and TB67S249FTG motor driver, and NEMA 17 and 23 motors. The project designed in this document is going to be an electrical redesign of the features within the RE-RASSOR shoulder project alongside adding new features such as a mesh networking system between rovers and a live video feed on the mobile application. Although inspiration can be taken from the RE-RASSOR's mobile application and their user interface, it is unlikely to be feasible to directly port their application and build a mesh network and video feed application on top of it due to different choices in hardware selection and therefore no guarantee for code to function properly within a different development environment. However, their software block diagram will prove to be a good point of reference as this project's use cases will be very similar in that commands for movement of the rover and other data will have to be sent via wireless communications.

### 2.3.2 ARCTURUS' AEROJET PAYLOAD (AUTONOMOUS ROVER) (SENIOR DESIGN FALL 2021/SPRING 2022 – GROUP 35)

This team's project involves the development of a fully autonomous rover that is able to carry a payload to a specified destination and then return back to its original location. Similar to the specifications pertaining to this project, the Arcturus project also implements live video transmission from the point of view of the rover. This team's implementation of the live video transmission limited themselves to a minimum of 400 ft, presumably for testing. Artificial intelligence was not implemented in this group's project, which means that object identification and predetermined pathfinding were not featured in the project. That said, their rover's autonomous actions were implemented to be limited to the following: self-waking capabilities

from sleep, recognizing the beginning of a descent to begin capturing video, sensing altitude and rate of descension, using RF signaling, GPS, or pathfinding to guide itself to the target destination, gathering sensor data, avoiding obstacles, and recognizing when it has returned to its starting point. Pertinent to this rover project, the Arcturus team set a minimum video resolution of 720i and a maximum resolution of 1920 x 1080, which is useful information on what resolutions are feasible given the constraints of costs and time within Senior Design. They also note that their rover's steady state condition for power consumption should ideally be less than 12 W/hr and during transient states (like acceleration and turning of the rover) the power consumption should be less than 20 W/hr. These values provide better context and reference for what values may be feasible in terms of power consumption when it applies to development in this rover project.

### 2.3.3 MOIST MESH-OPERATED IRRIGATION SENSOR TECHNOLOGY (UCF SENIOR DESIGN SUMMER 2018 – FALL 2018)

The MOIST (Mesh-Operated Irrigation Sensor Technology) project aims to overcome the inefficiencies of standard irrigation systems by incorporating a mesh networking system that accounts for the varying amounts of moisture within a given plane of grass. Our rover project involves incorporating a mesh networking system for communication between fixed-position communication towers and the rovers and between the rovers themselves. The MOIST team's mesh network is composed of the RF modules of each sprinkler node, the central server, and the solenoid that operates the hose. The server can be contacted by either the RF modules, the solenoid circuit module, and the web-app development stack. Each node consists of a microcontroller, RF module, solar panel, power control, sensor, and a battery. Similarly, the rover in this project will consist of an RF module (antenna), microcontroller, camera (sensor), and motors and their motor controller. The MOIST team opted for an external U.FL antenna for the purpose of boosting the range of the wireless connection of its nodes. As our project will also involve long-distance communication, it would be advisable for our project to incorporate an external antenna as part of our communications system if the built-in antennas on the selected boards prove to be insufficient. The ESP32-C6-WROOM microcontroller selected in our project would allow for any antennas that use the U.FL, MHFI and AMC connectors. In the same way that the MOIST nodes are interconnected with one another and to a base station, the rovers in our project will be designed to be interconnected with one another and to one, if not several, communication towers akin to the base towers in the MOIST project.

## 2.4 REQUIRED SPECIFICATIONS

*Table 2.1 Key Engineering Specifications*

<b>Specifications</b>	
<b>Parameters</b>	<b>Target Values</b>
Power Consumption	No more than 240 W (24 V, 10A)
Communication Rate	At least 500 KB/s between nodes
Battery Life	At least one hour given standard operating conditions*

Packet Loss	No more than 1% packets dropped for a given transmission
Video Quality	At least 480p resolution
Video Frame Rate (Processing Rate)	At least 45 frames per second
Rover Unit Weight	No more than 30 lbs
Communication Latency	No more than 1 minute RTT between nodes (for TBD byte message)
Communication Range	Attain a maximum range of 100 meters between nodes
Maximum Payload	20 kg (Lunar gravitational force)

## 2.5 HARDWARE BLOCK DIAGRAM

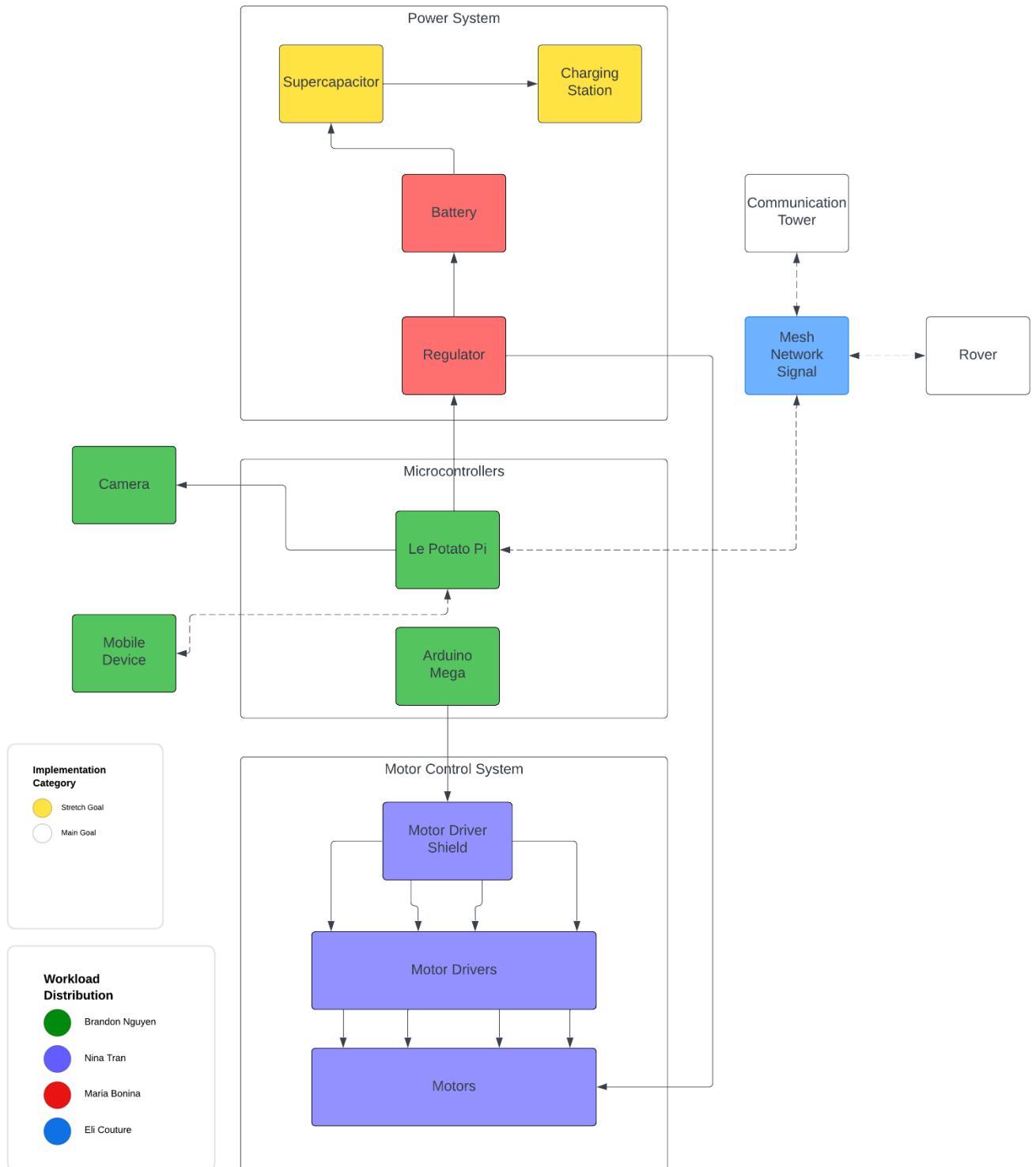


Figure 2.1 Hardware Block Diagram

## 2.6 SOFTWARE FLOWCHART

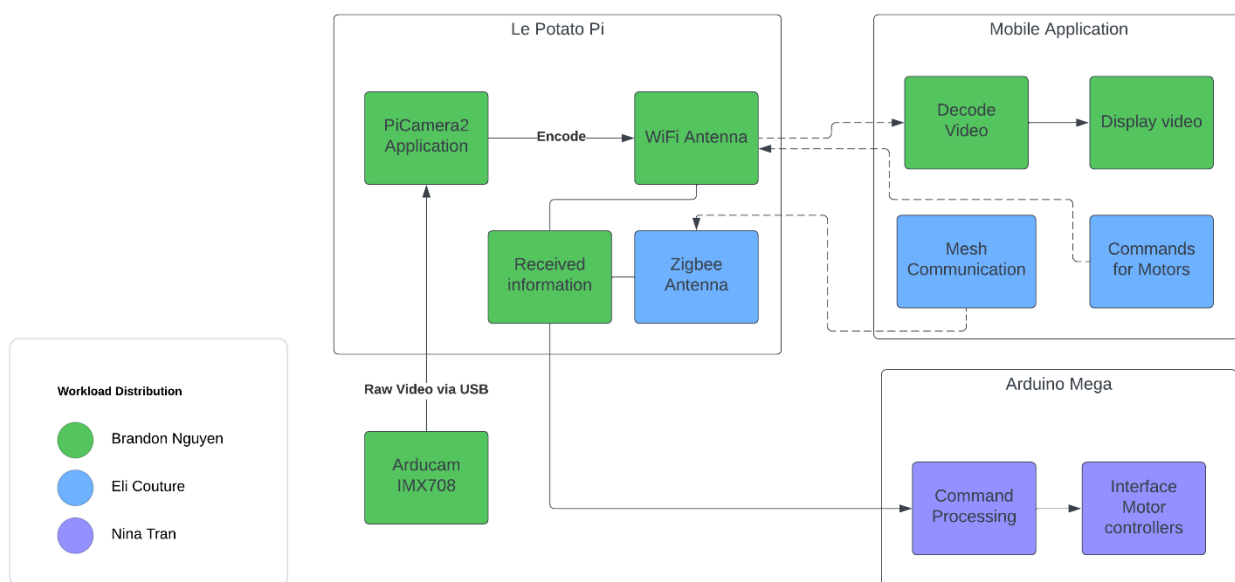


Figure 2.2 Software Block Diagram

## 2.7 HOUSE OF QUALITY

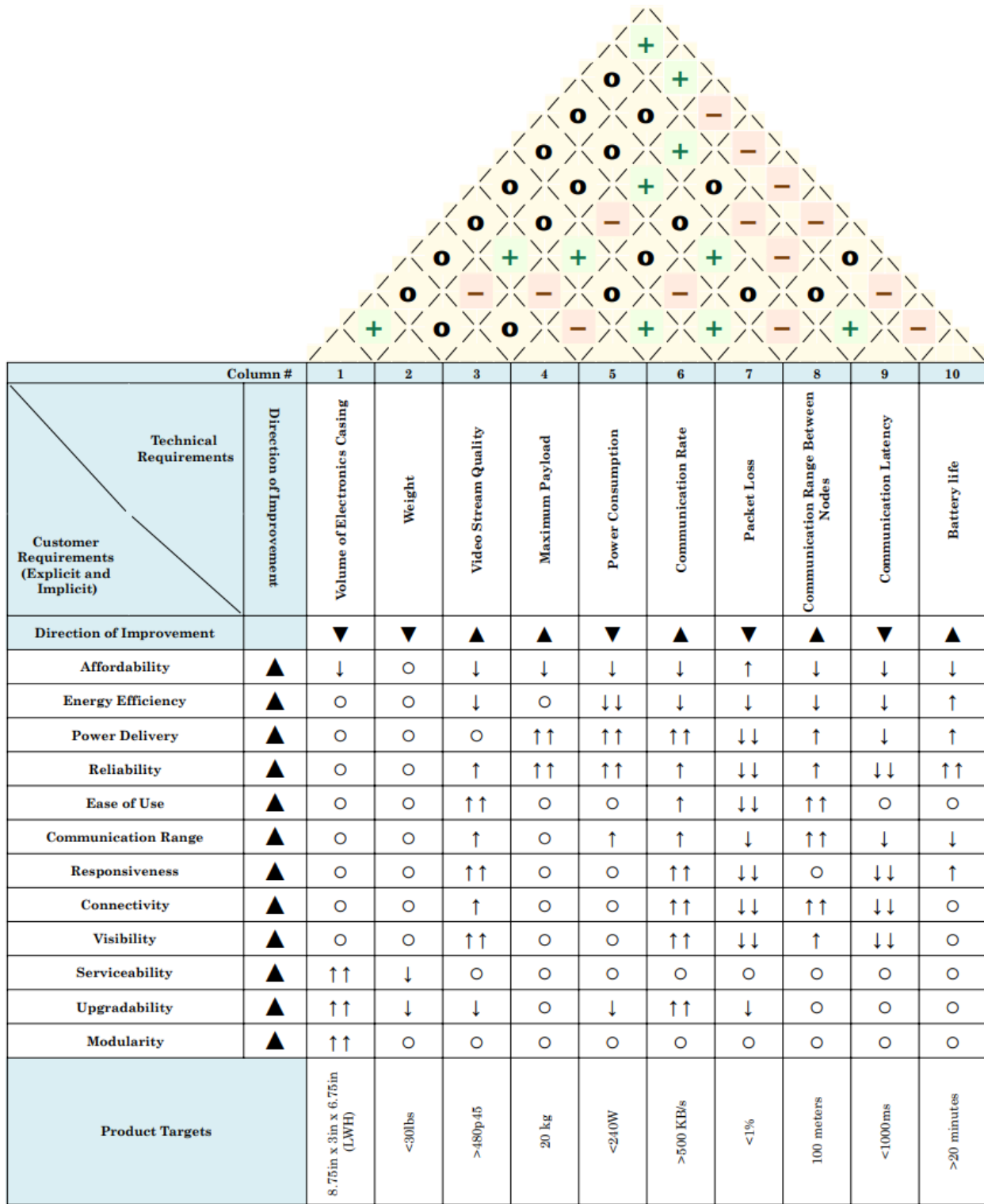


Figure 2.3. House of Quality

Correlation		Relationship		Direction of Improvement	
Positive	+	Strongly Positive	↑↑	Maximize	▲
Negative	-	Moderately Positive	↑	Target	◇
No Correlation	o	No Relation	o	Minimize	▼
		Moderately Negative	↓		
		Strongly Negative	↓↓		

*Figure 2.4 House of Quality Legend*

### 3 RESEARCH

#### 3.1 RELEVANT TECHNOLOGIES

##### 3.1.1 FIELD PROGRAMMABLE GATE ARRAYS VS. MICROCONTROLLERS

Field Programmable Gate Arrays are integrated circuits are manufactured in a way that allow end users to reconfigure the hardware to meet their needs in integration. They consist of a matrix of configurable logic blocks (CLBs) connected through programmable interconnects. This functionality distinguishes FPGAs from Application Specific Integrated Circuits (ASICs) which are what normal microcontrollers are classified as.

Field Programmable Gate Arrays offer greater efficiency in processing time and tight timings for time-sensitive operations. For example, take button polling. On a microcontroller, the processor would run a section of code that checks the status of the pin directed to the button and updates the state of another pin depending on how the programmer has set the functionality of the button press. By contrast, an FPGA can dedicate a piece of its hardware to purely polling the button, passing the value of the button to an input buffer, passing the data through the routing matrix and outputting through an output buffer. Similarly, to the microcontroller's looping code, this process occurs continuously all the time but, delays on the FPGA are significantly reduced because the only delays produced are due to the switching delays of the transistors in the chip. By comparison, the software polling method using the MCU would have higher delays due to other lines of code competing for processor time, whereas the FPGA has separate, independent pieces of hardware dedicated to the tasks previously mentioned.

There are two major setbacks to using field programmable gate arrays: cost and power. Field programmable gate arrays tend to be very expensive due to the manufacturing process requiring greater amounts of silicon compared to the amount used in manufacturing consumer electronics processors. Field programmable gate arrays also require a significant amount of research and development to be designed and have tooling available to fabricate them. Power consumption in field programmable gate arrays tend to be much higher than their Application Specific Integrated Circuits counterparts because of the sheer number of transistors required to build the look-up table structures in the FPGA. Even while designing your circuits on a FPGA to be power efficient, at idle, the Alchitry Au consumes approximately 100mA and under load, current rises over 1000mA. Now, comparing with the ATmega32U4 chip (used on the Arduino Leonardo), it uses a mere 27mA when running at max capacity with 5V.

Microcontrollers are integrated circuits that are designed to govern a selection of specific operations in an embedded system. Unlike FPGAs, they are considered an Application Specific

Integrated Circuit and are therefore do not have hardware programmability and follows the Von Neumann machine architecture.

Microcontrollers have several core elements that work together: the CPU, memory, and I/O peripherals. The CPU is responsible for executing operations and instructions pertaining to arithmetic, logic, I/O, and data transfer. The memory on the microcontroller is used for storing and fetching the data that the processor interacts with. There are two memory types: program memory and data memory. Program memory is non-volatile and is used to store long-term information about the instructions that the CPU executes. Data memory is volatile and used for temporary storage while instructions are being executed. I/O peripherals are devices that serve as an interface for the CPU to receive and transmit data to the outside world.

*Table 3.1 Microcontroller and FPGA comparison*

<b>Device Type</b>	<b>Microcontrollers</b>	<b>Field Programmable Gate Arrays</b>
<b>Architecture</b>	Von Neumann / Harvard architecture	Reconfigurable Logic
<b>Energy Consumption</b>	Typically, lower than FPGAs, viable for battery powered operation	Typically, higher than MCUs, not recommended for battery powered operation
<b>Ease of Use</b>	Easy to use programming languages with existing libraries, easily scalable with peripherals. High level features are pre-built.	Difficult learning curve and scalability due to narrow functionality of FPGA. Digital logic has to be built from the ground up.
<b>Versatility</b>	Limited to select I/O, communication standards, and other features depending on the MCU.	Virtually any digital circuit can be built using an FPGA
<b>Cost</b>	Much lower cost compared to FPGAs. Prices range from less than \$1 to \$50.	A much higher cost for development boards compared to MCUs. Prices range from \$100 to \$600.
<b>Application</b>	IoT deployments, robotics, automotive, building automation, manufacturing, etc.	Hardware prototyping, hardware acceleration, space avionics, neural networks

Field Programmable Gate Arrays, while offering the most versatility in being able to be programmed to replicate virtually any digital circuit, is not a feasible option for the purposes of this project due to cost, time, and energy constraints. Current market offerings for FPGAs are typically around \$100 to \$600 compared to microcontrollers which range from a mere \$1 to \$50 per unit. Time constraints are another consideration since learning to build the digital logic needed to interface with a camera, motor controller, and antenna for wireless communication on an FPGA would take too much time compared to using the pre-established communication interfaces built on common microcontrollers like UART, SPI, and I2C. Since a major design



constraint of the project involves the rover being battery powered, energy consumption rates are of upmost importance. As previously discussed, FPGAs consume more power compared to microcontrollers even at idle. Therefore, microcontrollers are the superior choice for the purposes of this project.

### 3.1.2 MICROCONTROLLER

A microcontroller is a type of integrated circuit chip that uses VLSI technology to integrate the CPI, RAM, ROM, various I/O ports, interrupt systems, timers, pulse width modulation circuits, display drivers, and more into a silicon chip to form a small and complete computer system. The microcontroller serves as the brain of the system, interconnecting the various components of the rover. Therefore, finding and selecting a microcontroller that best fits the use case of this project is of upmost importance in order to reduce costs by ensuring that most, if not all, features on the board are used and to ensure compatibility with the other components of the rover. The rover will be designed to assign the responsibility of interfacing the camera system, motor controller, and antennas to the microcontroller.

#### 3.1.2.1 COMPLEX INSTRUCTION SET COMPUTING VS. REDUCED INSTRUCTION SET COMPUTING

The processors (i.e., microprocessors) found on microcontrollers can be based on two different instruction set architectures: Complex Instruction Set Computing (CISC) and Reduced Instruction Set Computing (RISC).

The design approach with the CISC architecture is to allow for a single instruction to do several operations (i.e., load, store, evaluate) with the goal of minimizing the number of instructions per program. However, this is at the cost of generating a higher number of cycles per instruction.

The design approach with the RISC architecture is to make the hardware simpler by using a simpler instruction set that separates operations like loading and storing into separate instructions and therefore breaking operations into smaller steps instead of one chunk like in the CISC architecture. This reduces the number of cycles per instruction but at the cost of increasing the number of instructions per program.

CISC usually has around 80 instructions and a higher amount of (12-24) addressing modes compared to RISC with its ~30 instructions and 3-5 addressing modes. The CISC instruction set can be generally easier to implement and allow for more efficient memory usage at the cost of performance degradation due to its instructions requiring a higher number of clock cycles to execute. The RISC instruction set places a greater emphasis on software providing greater performance compared to CISC processors, that are designed with a focus on hardware, due to its simple instruction set and design simplicity. Below is a table that summarizes the differences between the RISC and CISC instruction set architectures.

*Table 3.2 CISC vs. RISC Architecture*

Architecture	CISC	RISC
<b>Design Emphasis</b>	Hardware	Software
<b>Instruction Count</b>	Large number of instructions	Small number of fixed length instructions

<b>Instruction Size</b>	Complex, variable-length instructions	Simple, standardized instructions
<b>Instruction Execution Time</b>	Instructions can span several clock cycles	Single clock cycle instructions
<b>Memory Efficiency</b>	More efficient use of RAM	Heavy use of RAM
<b>Space Efficiency</b>	Small code sizes	Large code sizes
<b>Cycles per Second</b>	High cycles per second	Low cycles per second

For the purposes of this project, the RISC instruction set architecture is the best option because interfacing the camera for live-feed video and developing a mesh network will involve a significant amount of software to be written, which aligns with how the RISC architecture is designed with a focus on software.

### 3.1.2.2 MSP430

Texas Instruments has several models within the MSP430 line of microcontrollers. They offer five different categories: general purpose, housekeeping, energy monitoring & management, ultrasonic sensing, and capacitive touch sensing capable microcontrollers.

Since the microcontroller on the rover is unlikely to be interfaced directly by the operator frequently, the capacitive touch sensing capable microcontroller is not of interest. Similarly, the ultrasonic sensing capable microcontroller is not of interest since the rover will not be made autonomous and therefore will not require that kind of data. Now, the general purpose, housekeeping, and energy monitoring & management specialized microcontrollers would fall in line with the purposes of the project: with housekeeping MCUs providing a solution to combining several discrete ICs into an auxiliary MCU to reduce costs and produce higher space efficiency on the PCB and the energy monitoring & management microcontroller aiding in managing battery life for the rover.

### 3.1.2.3 ARDUINO

Arduino microcontrollers come in three separate family of products: the Nano, MKR, and Classic Families. The MKR microcontrollers come with a radio module that enables Wi-Fi, Bluetooth, LoRa, Sigfox, and NB-IoT communication. Having support for these communication standards will provide a means to develop the mesh networking system between other rovers and communication towers. The shields and carriers within the MKR line of products serve to extend functionality of the boards and can provide environmental sensors, GPS, and motor control. Due to project constraints, it is a necessity to use an Arduino in order to use a RAMPS 1.4 kit, which is especially designed for the Arduino Mega microcontroller board, for powering and interacting with motor controllers.

### 3.1.2.4 RASPBERRY PI

Raspberry Pi's main microcontroller offering is the RP2040 which features a dual core 133Mhz processor, embedded SRAM, 30 pins for GPIO, support for UART, SPI, and I2C communication

interfaces which will be good for connecting peripherals, programmable I/O for extended peripheral support, 4 channel AC with 500ksps and 12-bit conversion, and a USB 1.1 controller.

Raspberry Pi also offers two microcontroller boards based on the RP2040 microcontroller chip: the Raspberry Pi Pico and the Raspberry Pi Pico W. The Pico board provides minimal external circuitry around the RP2040 chip to support interfacing the chip. The majority of the RP2040 pins are brought to the user IO pins on the left and right edges of the board. There are also C/C++ and Python software development kits (SDKs) available for the Raspberry Pi Pico.

Another offering manufactured by Raspberry Pi is the Pi Zero 2 model. The Raspberry Pi Zero 2 W provides a potential benefit in providing support for the CSI-2 interface and presenting an option to use CSI-2 microcontroller cameras. Like the RP2040, it supports 2.4GHz IEEE 802.11b/g/n wireless LAN, Bluetooth support, but additionally has an onboard antenna as well. Despite how feature-rich this board is, it might be too powerful for the scope of the project due to its 1 GHz quad-core 64-bit CPU and consumes too much power. However, this processing power may be justified if high resolution video processing becomes an attainable goal for the project. The Pi Zero 2 requires 5 V DC at 2.5 A to operate, which is higher compared to the other offerings from other manufacturers, which can operate as low as 3.3 V.

Another larger form factor offered by Raspberry Pi is the Raspberry Pi B series of boards. The Raspberry Pi 4 B supports the MIPI CSI-2 port which is an option for implementation in the camera application of this project as well as the H264 camera encoder/decoder format. The Raspberry Pi 4 B boasts a 64-bit 1.8 GHz processor that should provide plenty of headroom for video processing on top of the pre-existing functionality for operating the motors. The Raspberry Pi 3 B/B+ may also sufficiently meet I/O and processor speed requirements as well. To meet physical constraints brought by working with a pre-established mounting system for the microcontrollers, a Pi B form factor board must be selected in order to save on time and design costs.

### 3.1.2.5 ESP32

The ESP32 series of microcontrollers, created by Espressif Systems, is a low-power system on a chip (SoC). It features Wi-Fi, Bluetooth and on-board radio for wireless connectivity, several types of internal memory, and a vast peripheral I/O interface. The ESP32 has support for ADCs and DACs, I2C, UART, CAN (Controller Area Network) 2.0, SPI, PWM (pulse width modulation), and several other standards. The ESP32 is a 32-bit microcontroller that has options for either a Tensilica Xtensa LX6 microprocessor (dual-core or single-core) and a single-core RISC-V microprocessor. The ESP32 starts at 4 MB of flash memory but some models may have options for 8 MB or 16 MB. The ESP32 is also quite energy efficient and is able to operate in extreme temperatures, between -40°C and 125°C, which serves well considering the one of the main goals is to provide a proof of concept of a rover to be operated on the moon. ESP32 series microcontrollers are offered as three different types of modules: the WROOM, SOLO, and WROVER modules. The main benefit of choosing an ESP32 microcontroller would be its built-in support for many wireless communication standards as mentioned before and ultra-low power consumption.

### 3.1.2.6 STM32

The STM32 family of microcontrollers are based on various 32-bit RISC ARM Cortex-M cores created by STMicroelectronics. The line of microcontrollers (based on the ARM Cortex-M3 core) is divided based on their core architecture called the “basic”, “enhanced”, and “interconnected” series. The “enhanced” and “interconnected” microcontrollers operate on 72MHz clock frequencies and the “basic” series operates on a clock frequency of 36 MHz. Both the basic and enhanced series feature built-in flash memory of capacities between 32K to 128K. When running at 72MHz and executing code from flash memory, the STM32 consumes 36mA, or 0.5mA/MHz. The basic model of the STM32 microcontroller does not support wireless connectivity but the STM32Wx series microcontrollers do provide sub-GHz and 2.4GHz frequency range operation.

### 3.1.2.7 ALLWINNER

Allwinner Tritium H3/H5 provides a lower cost alternative to the Raspberry Pi B series microcontrollers while providing the same form factor as the Pi 2/3 B/B+, meeting sponsor constraints in adhering to pre-existing mounting solutions for the rover electronics housing. However, it does not support the CSI-2 camera interface which is highly desired for high bandwidth video transmission from the camera to the microcontroller. It does support the DVP Parallel Camera Interface which is a lower bandwidth alternative. The Tritium H3/H5 does have built-in 802.11 Wi-Fi nor Bluetooth capabilities. Although it does support the USB interface for implementing a camera, the Raspberry Pi 4 B outperforms this solution at a similar price point. For these reasons, the Allwinner ALL-H3-CC microcontroller does not serve to be the best microcontroller solution for the purposes of this project.

### 3.1.2.8 LIBRE COMPUTER

Libre Computer has a competitive alternative to the Raspberry Pi B series microcontrollers with the Le Potato Mini AML-S905X-CC board. This microcontroller meets sponsor constraints in that it is a Pi B form factor board allowing for compatibility with a pre-existing mounting system for the microcontrollers and meets Pi 3 B performance at a lower price point. The downside is that the microcontroller does not have the CSI-2 connector. However, this disadvantage can be subverted by converting any CSI-2 cameras that are used to the UVC interface with a simple converter board. The greatest advantage offered by this microcontroller is the availability of pre-existing software repositories that utilize this microcontroller from the Florida Space Institute. With permission, these software repositories can be utilized to more quickly establish a baseline for the project’s software requirements and staff at Florida Space Institute can provide support in the development of new software for this project.

*Table 3.3 Candidate Microcontroller Comparison*

<b>Microcontroller</b>	<b>Arduino MKR WiFi</b>	<b>Raspberry Pi Zero 2 W</b>	<b>ESP32-C6-WROOM</b>	<b>STM32F0x2</b>	<b>TI MSP430</b>
Word Size	32-bit	64-bit	32-bit	32-bit	16-bit
Wireless Capability	WiFi/Bluetooth	WiFi/Bluetooth	WiFi/Bluetooth/Radio	No	No
On-Board Antenna	Yes	Yes	Yes	No	No

Clock Speed	48 MHz	1 GHz	160-240 MHz	48 MHz	4-25MHz
Nonvolatile Memory	256 KB	microSD	4 MB	<=128 KB	<=512 KB
Volatile Memory (SRAM)	32 KB	512 MB	520 KB	16 KB	up to 66 KB
USB enabled	Yes (USB 1.1)	Yes (USB 2.0)	No	Yes (USB 2.0)	Yes
Power Requirement	3.3 V	5 V	3.3 V	2.0-3.6 V	3.3 V
Operating System	None	Yes (Linux)	None	None	None
GPIO Count	45 pins (incl. built-in LED pins)	40 pins	34 pins	28-100 pins depending on model	48-83 pins on FR6989
CSI	No	Yes	No	No	Yes
UART	Yes	Yes	Yes	Yes	Yes
I2C	Yes	Yes	Yes	Yes	Yes
SPI	Yes	Yes	Yes	Yes	Yes

Microcontroller	Raspberry Pi 4 B	Tritium H3/H5	Arduino Mega 2560	Le Potato AML-S905X-CC
Word Size	64-bit	32-bit/64-bit	8-bit	64-bit
Wireless Capability	802.11, Bluetooth 5.0	None	None	802.11 Wi-Fi
On-Board Antenna	Yes	No	No	No
Clock Speed	1.5 GHz	1.0 GHz	16 MHz	1.512 GHz
Nonvolatile Memory	SD card	MicroSD	256 KB (flash), 4KB EEPROM	MicroSD
Volatile Memory (SRAM)	1, 2 or 4 GB	512MB-2GB	8 KB	2 GB
USB enabled	Yes	Yes	Yes	Yes
Power Requirement	5V, 3A	5V, 2A	5V, 20mA per pin	5V, 2A
Operating System	Linux	Linux	None	Linux
GPIO Count	28 (user)	28 (user)	86	40
CSI	Yes	No	No	No
UART	Yes	Yes	Yes	Yes
I2C	Yes	Yes	Yes	Yes
SPI	Yes	Yes	Yes	Yes

### 3.1.3 CAMERA

#### 3.1.3.1 VIDEO COMPRESSION STANDARDS COMPARISON

There are several video compression standards that exist with varying benefits and setbacks. The three most prevalent standards today are the M-JPEG, MPEG-4, and H.264 (MPEG-4 AVC) formats. These different standards employ different approaches to achieving video compression: intra-frame vs. inter-frame compression. Inter-frame compression takes advantage of the fact that sometimes very little changes are made from frame-to-frame and reducing redundant image data in that regard. Intra-frame compression takes advantage of the fact that many blocks of pixels share very similar data and reduces redundancy of pixel data by grouping those similar blocks of pixels.

The M-JPEG employs intra-frame compression whereas the MPEG-4 and the H.264 standards use inter-frame compression.

*Table 3.4 Inter- vs. Intra- Frame Compression Comparison*

Technology	Inter-Frame Compression	Intra-Frame Compression
Area of Exploitation	Data reduction is done between frames, exploiting redundancy between successive frames.	Data reduction takes place within each frame, exploiting redundancy within a frame's own image data.
Redundancy Type	Temporal redundancy	Spatial redundancy
Processing Time	Requires longer processing time due to the need to analyze multiple frames	Requires less processing time because only a single frame is being analyzed
Relevant Standards	MPEG-4 and H.264	M-JPEG

*Table 3.5 Comparison of Compression Standards*

Compression Standard	M-JPEG	MPEG-4	H.264
Compression Factor	1:20	1:50	1:100
CPU Utilization	Low	High	High
Compression Technology	Intra-Frame	Inter-Frame	Inter-Frame
Motion Sensitivity	Compression unaffected by motion	Motion complexity throttles compression efficiency	Motion complexity throttles compression efficiency
Unique Advantages	Clearer images at lower frame rates compared to MPEG-4	Widespread compatibility across wide range of devices	Highly efficient in low-motion video content

Comparing the various standards, the H.264 standard has the highest compression ratio and therefore has the greatest efficiency by far with a 1:100 ratio. Although the M-JPEG standard may offer a clearer image, especially in capturing scenes with highly random motion, its compression ratio is significantly lower than that of the H.264 standard. Given that bandwidth could potentially be a bottleneck, a higher quality image at the cost of space efficiency may not be worthwhile if the WLAN cannot adequately transport the data in a timely manner. The high

CPU utilization of the H.264 standard can be mitigated by selecting a microcontroller that adequately meets the performance needs of the standard. MPEG-4 is another standard among the three listed in the table above, but it simply does not offer any worthwhile advantages over the H.264 standard at the cost of a halved compression factor compared to the H.264 standard.

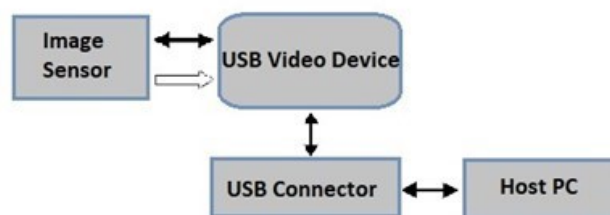
### 3.1.3.2 COMMUNICATION INTERFACES

Most cameras offered for use with microcontrollers either operate on the SPI (Serial Peripheral Interface), USB, Parallel Interface, GMSL (Gigabit Multimedia Serial Link) or MIPI CSI-2 interfaces.

The Serial Peripheral Interface is a four-wire bus consisting of a serial clock, master output/slave input, master input/slave output, and a device select pin. Although there is no standard specification for SPI, SPI can operate at speeds of up to 60 Mbps. However, this is still relatively slower than the other interfaces. The SPI interface is functional for distances of up to 10 meters, but beyond that, you must use a repeater to amplify the signal again. The biggest advantage with SPI is that it is compatible with virtually every microcontroller offered on the market today.

The MIPI CSI-2 (Mobile Industry Processor Interface Alliance Camera Serial Interface-2) specification describes the physical layer of the signal transfer as well as the CSI-2 protocol for image data transfers. CSI-2 provides a standard protocol for the configuration of the sensor/camera module in the form of the CCI (Camera Control Interface) which is physically based on I2C. MIPI CSI-2 camera modules are implemented using a flat flex cable through a board-to-board connection. The MIPI CSI-2 interface is typically used in applications related to machine vision, imaging, contextual awareness, biometric recognition, surveillance, and ADAS (advanced driver assistance systems). The MIPI A-PHY physical layer using CSI-2 v4.0 supports data rates of up to 16 Gbps. A major limitation of the MIPI CSI-2 interface however, is the fact cameras that utilize this interface rely on extra drivers to work resulting in limited support for different image sensors.

Cameras operating on the USB interface adhere to the UVC (USB video class) standard. The figure below is the block diagram of the USB video class application.



*Figure 3.1 USB UVC Block Diagram*

USB UVC cameras have the following advantages: support for several video formats such as YUV, MJPEG, MPEG-2 TS, H.264, DV, and others; availability of system-supplied drivers eliminating the need for external drivers; built-in generic class drivers to control video; and support for multiple video resolutions and frame rates, allowing for bandwidth negotiation between the device and host. USB cameras are also generally more inexpensive compared to MIPI cameras and have a built-in power supply which draws power from the USB connection itself.

Within the USB interface there are different generations of USB with varying levels of bandwidth. The table below compares the maximum theoretical bandwidth of each USB standard.

*Table 3.6 Varying USB Bandwidths across generations*

<b>USB Generation</b>	<b>Bandwidth (bits/sec)</b>
USB 1.0	1.5 Mbps Low Speed / 12 Mbps Full Speed
USB 2.0	480 Mbps
USB 3.0	5 Gbps
USB 3.1	10 Gbps
USB 3.2	20 Gbps
USB 4	40 Gbps

The most common USB cameras available are USB 2.0 cameras and USB 3.0 cameras. The table below describes the key differences between the two technologies:

*Table 3.7 USB 2.0 vs. USB 3.0 Comparison*

<b>Specifications</b>	<b>USB 2.0</b>	<b>USB 3.0</b>
Bandwidth	480 Mbps	5 Gbps
Compression	HD video requires compression	HD video without compression
Current	Delivers 500mA	Delivers 900mA
Communication	One-way communication	Two-way communication
Number of wires	4	9

The biggest limitation of the USB 3.0 interface is that you cannot operate high-resolution sensors at high speed due to its limited bandwidth compared to the MIPI CSI-2 interface. The USB interface also does not provide a dedicated video stream, so image data may be delayed or lost during transmission. Cable lengths on USB 3.0 are limited to 5 meters from the host processor as well.

The (Camera) Parallel Interface (CPI) consists of an I2C bus to control the interface and a parallel bus for the image data itself. The I2C bus is used to control the various registers in the camera module. The I2C communication interface consists of an SDA signal (data) and SCK signal (clock) and is driven by an MCU that serves as the I2C master to communicate with the camera's configuration interface. The parallel bus is an 8-bit unidirectional parallel link connecting the video data bus and the image sensor (camera). The camera sensor transmits Vertical SYNC (VSYNC), Horizontal Reference (HREF) and Pixel clock (PCLK) timing signals to be received by the controlling MCU. The VSYNC signal serves to mark the start of each frame with a high pulse signal. The HREF serves to signal when active image data is being clocked out for each scan line. The PCLK signal marks the output of image data at every rising edge. The microcontroller must have hardware support for the Camera Parallel Interface to use it. The MIPI Camera Parallel Interface has notably been made obsolete by the MIPI CSI-2 interface.

The GMSL interface uses the Serializer/Deserializer (SerDes) technique to provide data transmission over a single coaxial cable or differential pair cables to minimize the number of I/O

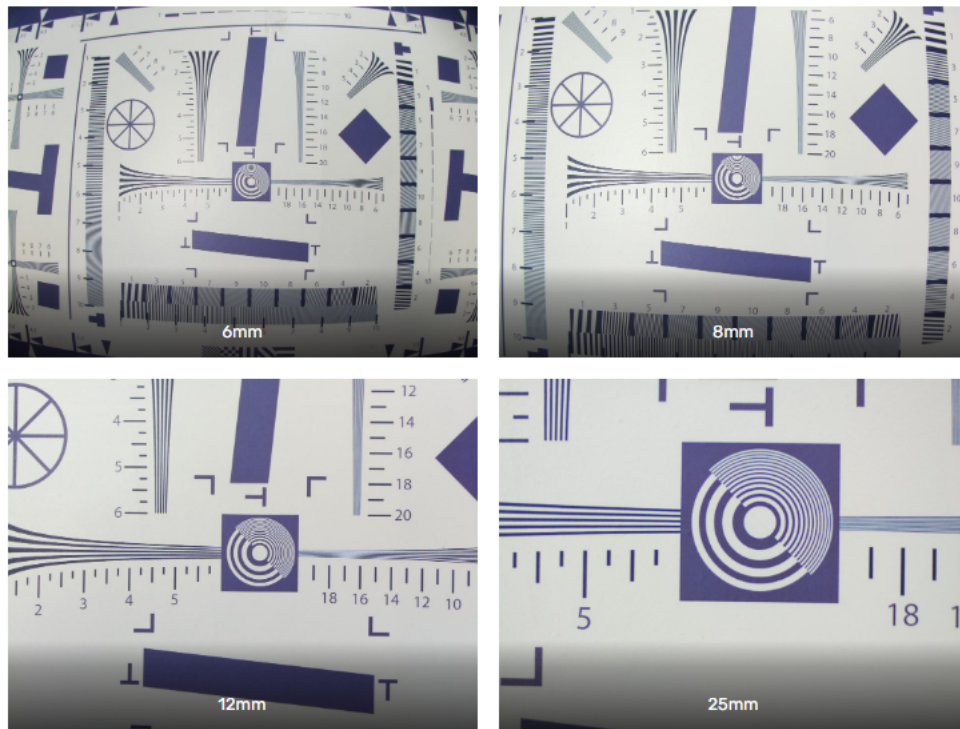


pins and interconnects. GMSL uses a serializer on the transmitting end for converting data into a serial stream and a deserializer on the receiving end to convert the serial data to parallel words for processing. The interface offers a maximum bandwidth of 6 Gbps. The GMSL has an advantage over the MIPI interface in that it allows for greater distance for transmission of signals. The MIPI interface can only support a max distance of 30 cm between the host processor and the camera module. By contrast, the GMSL interface supports cable lengths of up to 15 meters away through 50  $\Omega$  coaxial cable or 100  $\Omega$  STP while still supporting high frame rate video at low latencies. Since GMSL cameras are used for longer cable runs and have to be higher performing compared to the MIPI and USB cameras, they are typically more expensive than the MIPI and USB cameras.

Based on budget alone, it is easy to say that the GMSL interface falls outside of the scope of this project due to the sheer price of GMSL cameras, with each module costing at least \$300.

### 3.1.3.3 LENS TYPES

The various lens types all vary one factor: focal length. The focal length of a camera lens represents its ability to converge light. If a lens is better at converging light, then all the rays of light will converge at a shorter distance from the point of contact with the lens, creating a shorter focal length. Since more rays are able to converge to the image sensor, lenses with shorter focal lengths allow for a greater field of view compared to lenses with a longer focal length. The following figure demonstrates this effect.



*Figure 3.2 Image taken with various lenses of varying focal lengths*

There are four common lens types: the standard/normal, wide-angle, ultra-wide angle/fisheye, and telephoto lens. Camera lenses that are between 35mm and 85mm are considered standard lenses due to how they provide a field of view that is similar to that of the human eye. Wide-angle lenses

are lenses with a focal length of between 14mm and 35mm and provide a wide field of vision. Ultra-wide angle / fisheye lenses are lenses with a focal length of less than 14mm and provide an even greater field of view than the wide-angle lens to the point that the image begins to become bent and curved around the edges. Standard telephoto lenses are lenses with a focal length between 135mm and 300mm and function similarly to a telescope, offering great levels of magnification for an image.

#### 3.1.3.4 SHUTTER TYPES

There are two varieties of shutters in cameras: rolling and global. Rolling shutter cameras scan the image being captured line-by-line and then output the result. This can lead to commonly occurring distortion like motion blur from fast moving objects that change position within the camera's line of sight during the time between line scans during the image capture. Cameras with global shutters will instead capture light from every pixel in the scene at once, so images don't suffer from distortion, like motion blur. Global shutter cameras can also operate with shorter exposure times in ideal lighting conditions compared to rolling shutter cameras.

#### 3.1.3.5 AUTOFOCUS

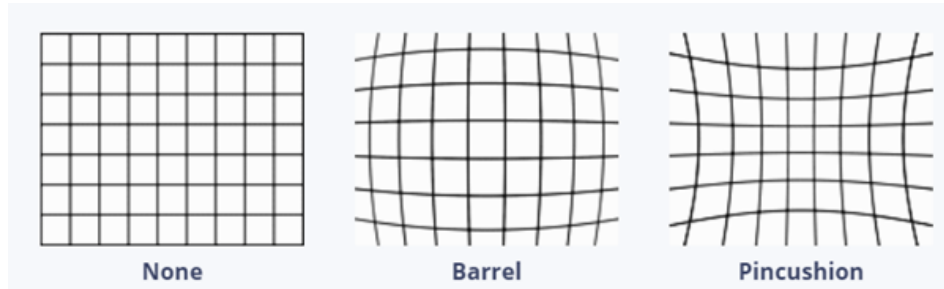
Raspberry Pi cameras have three prerequisites for implementing autofocus: having an image sensor, focus motor, and control system. The focus motor is responsible for moving the lens to obtain a clearer image or obtain focus. The control system is the method by which the microcontroller talks to the focus motor and obtains the desired focus in the scene. Fortunately, autofocus is a feature that is implemented by most microcontroller camera manufacturers.

#### 3.1.3.6 APERTURE

The aperture of a lens is expressed in terms of f stop numbers, which refers to the ratio of a lens' focal to its aperture's diameter and how much light is allowed to come into the lens. A lesser aperture or a larger focal length (f-stop) gives a greater depth of field. Depth of field refers to the blur made between the foreground (subject of the image) and the background, so a greater depth of field creates a stronger blur on the background while keeping the foreground clear. Since the aperture controls how much light is allowed to reach the image sensor, the ideal aperture size will depend on the amount of light in the environment.

#### 3.1.3.7 DISTORTION

Distortion is another consideration in determining the type of camera to select for this project. Distortion is the change in magnification from the center of the lens to the edges of the lens. There are generally two types of distortion: barrel distortion and pincushion distortion.



*Figure 3.3 Types of lens distortion*

Barrel distortion (negative distortion) is when points in the field of view (FOV) appear to be more magnified than the points around the edges of the field of view. Pincushion distortion (positive distortion) is when points in the FOV appear less magnified (or zoomed out) compared to the outer edges. These types of distortion occur when capturing images with wide-angle lenses but can be corrected to an extent by using compensating optical elements.

#### 3.1.4 POWER REQUIREMENTS

In recent years, the demand for higher density energy storage technologies has increased. This characteristic provides many benefits for an electronic system. Higher energy density can lead to a more extended runtime, allowing devices to operate for longer without the need to recharge or change batteries.

Another characteristic to be considered is the need for high efficiency. Some of the new power solutions can work but not be efficient enough to be used in an application. This factor has played a significant role in the rise of new technologies such as renewable energy. Although there is great need to switch to more environmentally friendly technologies, this can be difficult with the current efficiencies of this developing sector.

There are two main energy storage technologies to be evaluated for this project: batteries and supercapacitors.

##### 3.1.4.1 BATTERIES

###### 3.1.4.1.1 BENEFITS OF BATTERIES

Batteries are a very widely used technology with many chemistries such as lithium-ion and lead-acid. One of the advantages of batteries is their high density, which allows it to store more energy per mass unit than other energy storage technologies such as the supercapacitor. This can be important when having small space constraints. In our case, it will come down to whether it can fit in the existing rover space and how feasible it is to increase the electronics box.

Another benefit of batteries is the voltage stability. Due to their chemistry, batteries produce a stable output through their entire discharge cycle, which makes it simpler to ensure the required power is available for each device.

#### 3.1.4.1.2 BATTERY DRAWBACKS

One drawback for batteries is the relatively slow charging rate compared to supercapacitors. In this application, this will not play a significant decision factor since there is no charge speed requirement. Although this may need to be considered for future developments. In the case a rover needs to operate day and night, battery charging will need to be charged much faster. For now, the rover is designed to operate during the day, which makes the charging rate less significant.

#### 3.1.4.1.3 IMPORTANT CHARACTERISTICS

There are two main variables when looking at batteries: voltage and amp-hour. Voltage is a crucial variable to control when creating a system. It is important to ensure that all devices are being operated at the correct voltage and are being regulated to maintain it. However, this cannot be the only metric being measured. A high voltage with a low current can still not satisfy power requirements for a device. And a high voltage with a high current may deliver too much power as well as cause permanent damage. For this reason, we also analyze the amp-hour when looking at batteries. Amp-hour is a measure of capacity or total energy of a battery. It is an indicator of how many amps of current a battery can supply per hour. Together, these two variables give a great indication of how much power will be delivered by the battery.

There are many other characteristics that can be analyzed when looking into batteries. One of them is the discharge rate, also known as C-rating. This represents the speed it takes for the power to be discharged in relation to its total capacity. The higher the C-rating, the faster the power will be used. A high C-rating is beneficial to applications that require high power outputs such as electric tools. For this project, it would be beneficial for the motors, but not for any of the other devices. Besides, the motors don't need such a high-power output. The highest power constraint will be to drive long distances and climb mountains. For those two applications, the motors will not need a high torque. Therefore, this variable will not be taken into account.

Another characteristic to be analyzed is the cycle life of the battery. This measures the amount of times a battery can be charged and discharged until it starts causing significant damage to the battery performance. This measure can be important for applications that require a long product lifetime. For this project, there is no specific requirement for product lifetime. Although it would be ideal for the parts to last as long as possible, it can become expensive to make such an investment. With energy storage technology evolving fast, it may be wiser to later invest in a more efficient battery when the technology is more developed. For this reason, this variable will not be taken into consideration when choosing a battery.

Another variable is the temperature range. Batteries can operate significantly better or worse in different temperatures. When on the moon, this may become an important factor to consider since there is such a wide range of temperature. At night, temperatures on the moon can get extremely low, which will affect the charging. During the day, the temperature will increase and affect the performance of the battery when operating under the sun. The battery is planned to be enclosed, which will provide some physical protection from the harsh environmental conditions. This factor will be highly considered as the physical characteristics of the battery are evaluated. Ensuring the operating temperature is within the normal conditions of the moon will be a critical factor in determining the best solution.

Within batteries, there are many types of chemistries with different benefits and drawbacks. Some types of chemistry available in the market are lithium ion, lithium polymer, lead acid, alkaline, and others. These types have different benefits that will be analyzed relative to this project in the following paragraphs.

#### 3.1.4.1.4 LITHIUM-ION BATTERIES

Lithium-ion batteries are popular for their high energy density. This chemistry can provide significantly more power in a smaller package, facilitating the requirements for weight and space. This characteristic is very important for this application since the rover needs a high amount of energy to be able to drive for longer distances. Also, to be able to climb mountains while carrying the communications tower.

Another benefit of this chemistry is the long cycle life. The long durability makes this a more reliable and cost-effective choice. Lithium-ion batteries have a fast-charging rate. This can be important for other tasks that require the device to be operating for a large portion of the day and does not have time to spend charging. In this application, this is not a limitation. The rover will not benefit from fast charging since there is a long amount of time for tasks to be done. The rover can be left charging overnight and whenever it is not being used.

One of the most important characteristics of lithium-ion batteries is their extremely high efficiency, at nearly 100[MLB1] %. Especially when compared to other battery chemistries, this value may become very impressive. For this project, we have a theoretically infinite energy resource. For this reason, efficiency may not be a top priority. Although it is always important to design the system to be as efficient as possible.

The benefit mentioned above comes at a high cost. One of the drawbacks from this chemistry is the high cost of manufacturing and materials, which increases market price. This may be an issue for this project since there is a constrained budget. Considering the need for a relatively high amount of power for a small application, there may not be enough funds to afford an expensive battery.

#### 3.1.4.1.5 LITHIUM POLYMER BATTERIES

Another type of battery that could be used for this project is lithium polymer. Due to its different chemistry, this battery has much better safety properties. This type of battery has a significantly lower risk of combustion or explosion. They also often include safety features such as monitoring and protection circuits. This characteristic is important considering that on the moon there will not be availability for replacement parts. There will not be humans around, but it is still important to protect the condition of the battery as well as all other parts of the rover. If the battery combusts or explodes, it would damage all the electronics as well as the physical structure of the rover, which would likely melt.

Another positive characteristic is the shape's versatility. This means that the battery can be molded in multiple different ways to create new shapes and sizes according to the available space. This may be beneficial for the rover since there is a limited area designated for the electrical equipment that may not be suitable for existing batteries with less versatile chemistry.

Lithium polymer batteries also are lightweight. This factor is very important for this project. The lighter the rover, the less energy it will require to drive it up a mountain with an extra load. The battery will likely be the heaviest component of the rover; therefore, it is important to keep it light. Lithium polymer batteries also have a high energy density of about 185 to 220 Wh/L and 140 to 200 Wh/kg. For comparison, lithium-ion batteries have 250-270 Wh/kg. Lithium polymer batteries have moderate efficiency. The average is about 88%, [MLB2] which may be interpreted as low or high depending on the type of battery.

One of the disadvantages of using lithium polymer batteries is the sensitivity to high temperatures. Due to the more flexible packaging, the battery is unable to withstand high temperatures, damaging the performance and integrity of the battery. The operating temperature for lithium polymer batteries ranges from 0°C to 60°C. It is a relatively smaller range when looking at other chemistries. There is a much smaller tolerance to lower temperatures. For reference, lithium-ion batteries can withstand as low as -20°C.

#### 3.1.4.1.6 LEAD-ACID BATTERIES

Another type of battery chemistry is lead-acid. This chemistry is one of the most cost effective within the battery types. The materials used for this battery are lead and sulfuric acid, which are both inexpensive materials. For comparison, the cost of lead-acid batteries can range from \$150 to \$300 [MLB3] per kWh of storage capacity, while lithium-ion batteries can cost between \$350 to \$600 per kWh of storage capacity. This shows that lead-acid is about half of the cost of lithium ion. This is very important considering there is a constrained budget for this project. The efficiency for this battery is around 85% [MLB4], which is low compared to lithium ion.

Lead-acid batteries have been around for over a century. This means that there has been multiple applications, experiments, developments, and research on this battery chemistry. The well-established technologies tend to be much more reliable and trusted. Along with other characteristics, this makes the lead-acid batteries a great choice.

Another characteristic of lead-acid batteries is the high-power output. Lead-acid batteries are commonly used for applications that require high-power bursts. This has previously been discussed. For this project, this characteristic is not a major requirement since the rover does not need to have a high torque. Therefore, this will not be considered a high priority. Lead-acid batteries also have relatively high discharge rates, another factor that contributes to the ability to provide quick bursts of power. As discussed before, this is not a high priority.

Lead-acid batteries are known for being durable and robust. This makes them more suitable for environments with harsher physical conditions such as vibrations and high temperature variations. One example is marine applications. Lead-acid batteries are often used in that scenario especially due to their known durability. This characteristic includes a wide operating temperature range. A typical lead-acid battery can operate within a temperature range of -20°C to 60°C without significant performance degradation. This characteristic is very important for this project. Since the rover will need to be able to withstand the harsh environment on the moon, but most importantly the wide temperature range. For this reason, this battery chemistry may be a great choice [MLB5].

Another characteristic of lead-acid batteries is their recycling properties. This type of chemistry makes the battery highly recyclable. Many battery chemistries may use toxic chemicals that make them hard to dispose of. However, lead-acid batteries are made from lead and other materials that can be reused from older batteries as well as recycled into other lead-based products. It is important to consider the environmental impact of batteries, especially considering the current environmental challenges with battery disposal. Although if not recycled, lead and sulfuric acid can be very harmful to the environment. There is a proper method to produce, use, and dispose of the battery to avoid these negative impacts[MLB6] .

Lead-acid batteries also have a long lifetime. If properly maintained and used, they can last from three to five years all the way to twelve or more. This requirement is important for this project, since it is better for the rover to require less part replacements over the years[MLB7] .

Lead-acid batteries are also very safe. There is a low risk of thermal runaway as well as combustion, especially relative to other battery chemistries. This makes it a safer battery to use around humans. For this project, it will make it less likely to damage the electronics as well as the rover itself. Lead-acid batteries are also widely available. Due to its long history, the battery is now sold in various sizes, configurations, and is made by numerous manufacturers around the world. Lead-acid batteries are widely available in the market[MLB8] .

There are also drawbacks to lead-acid batteries. One of them is the weight and size. Relative to other available battery chemistries, lead-acid batteries can be considered heavy and bulky. In this project, where weight can be a limiting constraint, this may be an issue. The heavier the battery weighs, the harder it will be for the rover to travel the required distance and reach the top of mountains while carrying a load.

Lead-acid batteries have a relatively low energy density. This characteristic is related to the previously discussed. The battery may need to be larger and heavier to provide the same power as a battery with another chemistry. Lead-acid batteries have lower energy density than both lithium ion and lithium polymer batteries. Lithium-ion batteries typically have an energy density ranging from 150 to 250 Wh/kg and 300 to 700 Wh/L, depending on the specific chemistry and design. Lead-acid batteries typically have an energy density ranging from 30 to 50 Wh/kg and 50 to 100 Wh/L.

There are maintenance requirements that must be met in order to keep the performance and expected battery life. Some maintenance may include monitoring electrolyte levels, maintaining proper charging voltages, and checking and equalizing cell voltages. Lead-acid batteries have a limited life cycle. The number of cycles for typical lead-acid batteries is much lower than lithium-ion batteries. This means that the lifetime of this type of chemistry may cause the battery to need more frequent replacements.

#### 3.1.4.1.7 LITHIUM IRON PHOSPHATE

Lithium Iron Phosphate batteries are one of the most used batteries at this time. Some of the most important advantages of using this chemistry is the lighter weight. For this project, weight is very

important, since an increase in weight would increase the power consumption of the rover. The cost is moderate compared to other chemistries such as lithium ion and lithium polymer.

In terms of maintenance, there are some good charging habits that can help with prolonging the life of the battery. Although there are no specific maintenance requirements. This type of battery chemistry has a relatively low environmental impact.  $\text{LiFePO}_4$  has a higher discharge current and does not explode under extreme conditions.

The typical energy density of a lithium iron phosphate battery is from 100 to 120 Wh/kg and around 110 Wh/L. The density is higher than the lead acid chemistry, although lower than both lithium ion and lithium polymer. The efficiency of this battery is very competitive, at around 90% it puts this chemistry above all but the lithium-ion battery. The life cycle of lithium iron phosphate batteries is typically around 1200, which is much higher than any of the other chemistries analyzed in this section.

#### 3.1.4.1.8 SUMMARY

Below is a summary table of the most important factors discussed in this section. The lead acid battery is considered the most affordable option, as well as the least environmental impact. However, it has much lower density than the others, which contributes to its heavy weight. Lead acid batteries are also the only chemistry that requires maintenance. This may be a problem for this application since it would be difficult to conduct maintenance with the small crew and physical limitations such as the space suit. The operating temperatures are relatively the same, with the only difference being the lithium polymer with a smaller lower range. For this project, none of the technologies available in the market would be able to sustain the wide temperature range of the moon. For this, there must be more research done on how to increase the operating range of a battery through electronics, physical protection from the environment, or other options. In terms of efficiency, the lithium-ion is much greater than the others. This characteristic is important for this project since the battery needs to provide enough battery for all the high energy requirement roles of the rover such as climbing mountains, carrying other objects, and traveling long distances. Lead acid battery has the lowest life cycle, followed by lithium polymer, lithium-ion and lastly lithium iron phosphate. Having a high life cycle will lead to less spare part requirements, which may be difficult to have on the moon. The other characteristics are still important for reference but will not play a significant role in the battery chemistry choice.

Table[MLB13]

*Table 3.8 Battery Technology Comparison*



Characteristic	Lithium-Ion	Lithium Polymer	Lead-Acid	Lithium Iron Phosphate[MLB9]
Cost	Moderate to High	Moderate to High	Low to Moderate	Moderate
Maintenance	None	None	3 to 6 months	None
Environmental Impact	Low	Low	High	Low
Energy Density (Wh/kg)	150 to 250	140 to 200	30 to 50	100 to 120
Energy Density at 20°C (Wh/L)	~ 425	~ 385	~ 90	~110
Weight	Moderate	Moderate	Heavy	Moderate
Operating temperature	-20°C to 60°C	0°C to 60°C	-20°C to 60°C	20°C to 60°C
Efficiency	Nearly 100%	85%	88%	Around [MLB10] 90%
Life cycle	500 to 1000	300 to 500	200 to 300	Around 1200
Self-discharge rate at 20°C (% loss per month)	2%	2%	4% to 8%	2[MLB11] %
Internal Resistance (mΩ)	150 to 250	200 to 300	Less than 100	100[MLB12]

For this project, we will be using the lithium iron phosphate chemistry. This decision was made based on the low environmental impact, high energy density, high efficiency, and many other characteristics discussed above. Another important factor is the current market availability. Since this project will be completed in a tight timeline, it is important to have a short lead time.

#### 3.1.4.2 SUPERCAPACITOR

Supercapacitors work as storage elements that release energy through electrostatic charge. Note that supercapacitors [MLB1] are also called ultra-capacitors and electric double-layer capacitors.

One of the main characteristics of supercapacitors is the high-power density. This technology is great for delivering fast bursts of power. This may not play a large role for this application considering that the torque for the rover does not need to be higher. Although this may be important for future versions of the project.

Supercapacitors are also known for their long cycle life. The storage device can be charged and discharged millions of times before causing significant degradation to the device. This may play a

significant role in this application considering that this rover may need to be charged and used multiple times. Especially when sent to outer space, part replacement may become difficult. For these reasons, it may be wise to choose a technology with a longer lifespan to sustain a higher number of charging cycles.

Supercapacitors are also able to withstand a large range of temperature without impacting the performance of the device. This can be important when operating under harsh conditions. Supercapacitors tend to have operating temperatures ranging from -40 to 70 degrees Celsius. This is a much wider range compared to batteries such as lithium-ion batteries that have operating temperatures of about -20 to 60 [MLB2] degrees Celsius, although it is usually recommended to keep it between 10 and 30 degrees Celsius for a better lifetime. Taking this into consideration, this technology has a great advantage. For this application, the rover should be able to operate under the environmental constraints of the moon. During the day, temperatures can go as high as 120 degrees Celsius. At night, it can drop to as low as -130 [MLB3] degrees Celsius. No type of battery storage element is designed to handle this level of temperature range, although it is still beneficial to choose the one with the widest range.

One of the disadvantages of supercapacitors is the low energy density. This means the rover would need to be charged more often or a much larger arrangement of supercapacitors would need to be used. For our application, this plays a major factor. Low energy storage would limit the distance of the rover's path from the charging station. It would also limit the size of the mountain it is capable of climbing. The solution to this problem would be to either increase the amount/size of supercapacitors used and increase the volume designated for energy storage in the rover.

Another drawback when using capacitors is voltage limitations. When using a battery, it is common to use a single one, since they are available in the desired voltage. Supercapacitors are not widely available in the desired voltage. This means that more than one supercapacitor would need to be connected in series in order to reach the desired voltage. This may not be an issue since there is enough area to store more than one supercapacitor.

One of the largest constraints for the use of this technology for this product is the low efficiency. There have been experiments [MLB4] with supercapacitors that proved to be as high as 77%. This may be considered a high percentage for a system using supercapacitors, but it is much lower than the efficiency for lithium-ion batteries and lead acid batteries mentioned previously, which range much closer to 100%. As of this year, the cost of supercapacitor technology is high due to low volumes of production. Over time, the cost will tend to increase as the technology and manufacturing improves.

Below is a table for the comparison between these two main types of technologies.

*Table 3.9 Battery and Supercapacitor Comparison*

<b>Characteristic</b>	<b>Batteries</b>	<b>Supercapacitors</b>
<b>Energy Storage</b>	High energy density	Low energy density
<b>Power Output</b>	Relatively slow discharge	Rapid discharge
<b>Charge/Discharge Rate</b>	Moderate charge/discharge	Fast charge/discharge

<b>Cycle Life</b>	Limited cycle life	Excellent cycle life
<b>Energy Efficiency</b>	Generally high	High
<b>Operating Temperature</b>	Normal range	Wide range
<b>Cost</b>	Moderate to high	High initial cost, lower operating cost
<b>Environmental Impact</b>	Some battery chemistries can be harmful	Generally, more environmentally friendly
<b>Self-discharge Rate</b>	Some batteries have significant self-discharge	Negligible self-discharge

For this project, supercapacitors will be considered a stretch goal. This decision was made since it is important to have a highly reliable first version of the power system to ensure the functionality of the other systems in this project. A future version may be created that uses supercapacitors due to all the great benefits mentioned above, especially the remote charging. This option will be more feasible to use in the future when the technology is more efficient and better developed. For these reasons, the battery will be used for the first version.

### 3.1.5 REGULATOR

When designing an electronic system, regulating voltage is an extremely high priority. Regulators are used in almost every possible application for this purpose. It is responsible for maintaining system stability as well as efficiency. The two types of regulators are linear and switching, both used in different applications but for the same purpose. For this project, the regulator must be able to handle 24 volts and step it down as needed for each component. Some components such as the MCU and the motor drivers may have an operation voltage lower than 24 volts. The regulator must also be as efficient as reasonably possible, so that there is minimal loss of energy. Both regulators will be studied and compared under these important characteristics.

#### *Linear Regulators*

One of the important factors to be analyzed is PSRR, which stands for ripple rejection ratio. This value represents how much of the ripple from the input is being rejected by the regulator. For linear regulators, the PSSR is calculated by comparing the input and output ripple. It can also be calculated by comparing the open loop gain from the feedback loop and the gain from input to output voltage. This is represented in the following formula[MLB1].

Linear regulators, also referred to as LDOs, [MLB2] work by using a closed feedback loop to bias a pass element. The circuit usually consists of transistors, operational amplifiers, resistors, and capacitors. Linear regulators have a simple design compared to switching regulators. It requires much fewer external components, making it easier to design and implement. This simplicity leads to a more reliable system since there are less components in risk of failure. It also leads to a simpler troubleshooting time.

The ratio between voltage input and output is an important factor to consider. With linear regulators, the ratio cannot be greater than one since the output voltage cannot be higher than the input voltage. The closer the ratio is to one, the less power dissipation there is. For this reason, linear regulators are considered best as the ratio increases.

Linear regulators also have a low voltage ripple [MLB3] and noise. In applications with low voltage or sensitive audio components, having noise can negatively impact the efficiency of the system. This type of regulator also has low electromagnetic interference (EMI). This is because linear actuators operate continuously, while the other type has components that switch on and off. Having EMI can cause signal degradation, system errors, and can reduce the lifetime of components. Due to the characteristics mentioned above, this regulator is most often chosen when working with low voltage systems.

Linear regulators fit best for certain applications. In a project that requires a low-cost solution, a switching regulator may be out of budget. As mentioned above, applications that have noise sensitive components would require a linear regulator.

One of the key factors when using linear regulators is thermal considerations. Linear regulators can generate a lot of heat and require heat sinks. The easiest way to calculate if a heat sink is needed is by calculating the power dissipation. This can be found by multiplying the voltage drop across the regulator by the current passing through it. This will result in the number of watts being released by the regulator. If that number is high, a heat sink should be added to ensure there is not too much heat being released. One way of preventing this issue is by ensuring that the regulator is within its operating voltage as well as temperature. If it still is unclear whether a heat sink is needed, it may be best to find the thermal resistance values from the data sheet and ensure they are within range.

There are two types of startups for LDOs: current and voltage soft-starts. Current soft-start works by raising the current limit, which will slowly raise the output voltage while the output capacitance increases. The advantage of using this way is that the input current will flow consistently and not cause any load-current transients. The other way is voltage soft-start, which works by slowly raising the regulation voltage. This will cause a slow and consistent rise of the output voltage, with no voltage transients. The benefit of using this method is that there will be less resets. A reset happens when the output voltage crosses the load undervoltage threshold. Since this should only happen once during this method, there should be just one reset. The drawback of using this method is that the current will not be controlled, since it is dependent on the load. The graph below shows both ways as a function of time. The current is the variable being controlled on the current soft-start, since there is a steady growth in current and an exponential growth of voltage with some resets due to the undervoltage threshold. It can be observed that every time the output voltage reaches that threshold, the regulator goes into reset state, bringing the voltage back down. On the voltage soft-start graph, we can observe the linear rise of the output voltage, since the voltage is the variable being controlled by the regulator. Note that the regulator only enters reset state one time.

Image[MLB4]

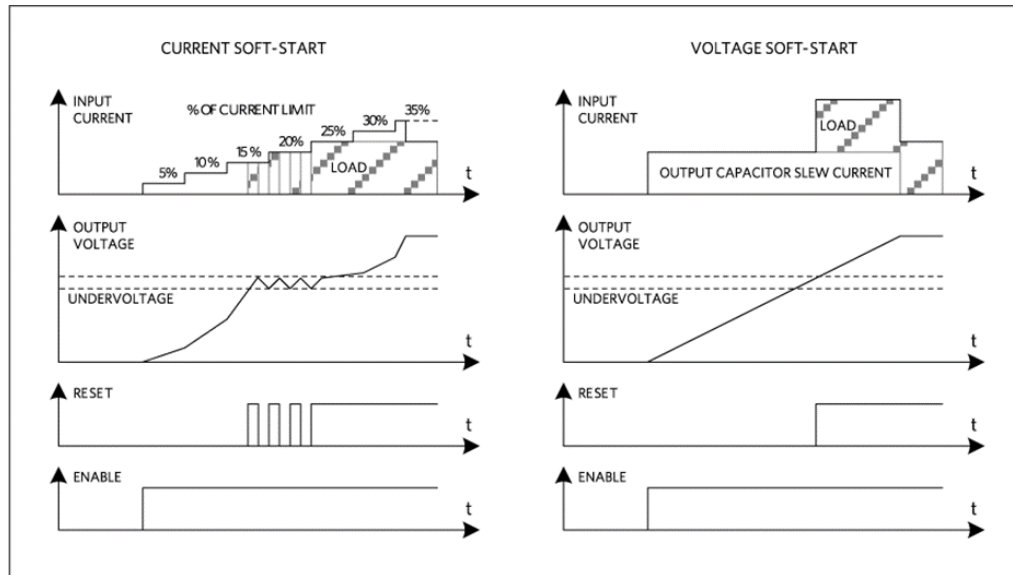


Figure 3.4 Current and Voltage Soft-Start Graphs

### Switching Regulators

The other type of regulator is the switching [MLB5] regulator. The circuit is composed of a power switch, an inductor, diode, and other components. The power switch is usually a FET. There is a switching controller IC responsible for monitoring the output voltage through a feedback control loop. There are three main advantages of using a switching regulator over a linear regulator.

One of the most significant advantages is the higher efficiency of the switching regulator. There is about 95% efficiency in switching regulators compared to around 65% on a linear regulator. This difference can be a deal breaker for projects that require minimal power loss to operate. For this project, the efficiency is not a deal breaker. Although it is important to keep the system as efficient as possible, the rover can properly operate with the less efficient option.

The most popular type of switching regulator is the buck converter. There are also other types such as the boost converter and the buck-boost converter. The main difference between them is the voltage scaling. The buck converter is used as a step-down regulator. The boost converter is used as a step-up regulator. The buck-boost regulator can be used for both functions. For this application, the one to be used would likely be the buck converter. There is no need to step up the voltage for this application. The other electronic components of the rover operate at a lower voltage than supplied by the battery, therefore stepping down will be required for some elements.

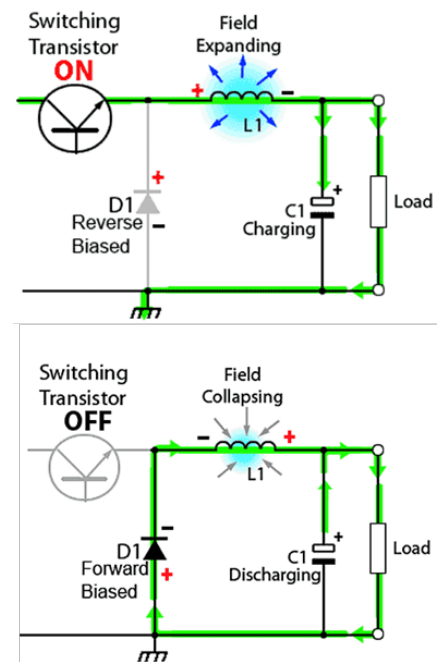


Figure 3.5 Switching Regulator Circuit Diagram

To maintain continuous voltage output[MLB6] , the buck converter will store energy in the inductor and use it when needed. This operation is sometimes called the Flywheel Circuit. This means that the circuit will keep “spinning” at a steady rate even with the pulses of energy from the electricity, just like a flywheel keeps its regular pace. The flywheel circuit is composed of a diode, an inductor, and a capacitor. The image below shows how those components are connected to the transistor and the load. When the switching transistor is on, the inductor will start storing energy, keeping the load from immediately reaching its peak voltage. While the transistor is on, there is a large voltage across the diode, which makes it reverse biased and not active. When the transistor is switched off, the inductor’s polarity is in reverse polarity, which means the energy from the inductor is being released as an electromagnetic field to the load voltage. The diode is now forward biased, which allows current to flow from ground to the inductor. As the energy in the inductor runs out, the load voltage starts to lower. This calls for the capacitor to start releasing its stored energy to the load so that it maintains voltage until the transistor turns on again. This process of turning the transistor on and off is what makes this a switching regulator. The energy storage components such as inductor and capacitor are responsible for maintaining voltage during the switch process.

*Table 3.10 Linear vs. Switching Regulator Comparison*

<b>Characteristic</b>	<b>Linear regulator</b>	<b>Switching regulator</b>
<b>Efficiency</b>	Low (usually 60% to 70[MLB7] %)	High (usually 95%)
<b>Complexity</b>	Simple	Needs external control circuitry
<b>Pricing</b>	Affordable	More expensive
<b>Thermal consideration</b>	More likely to need heat sink	Less likely to need heat sink
<b>Scaling</b>	Only step-down	Step-up or step-down
<b>Max. voltage output</b>	Low	Moderate to high
<b>PSRR (changes with frequency)</b>	Broadband, up to ~70 dB	About 50 to 100 dB
<b>Noise</b>	Low frequency noise that matches input ripple	Ripple on the output

The table above summarizes the factors discussed in this section. As discussed previously, the efficiency of the switching regulator is much larger than the linear regulator. The table also points out that switching regulators are more complex, which consequently makes them more expensive. The simplicity of the linear regulator also means there must be more considerations when planning for thermal conditions and the output voltage has more limitations. One of the largest drawbacks of switching regulators is the PSRR value. On the table, it is shown that depending on the specific model of the regulator, it may have a lower PSRR than that of the linear regulator.

## *Conclusion*

For this project, we will be using switching regulators. The main reason for this choice is because there is a lot of power going through these regulators, so efficiency is very important. Switching regulators are designed to be more efficient than switching regulators. Although more expensive, the price is within the project budget and will be worth the cost.

### 3.1.6 MOTORS

#### 3.1.6.1 GENERAL TYPES OF MOTORS

##### 3.1.6.1.1 AC MOTOR

AC motors play a fundamental role in various industries by converting Alternating Current (AC) electrical energy into mechanical energy. This process is facilitated by the change in polarity of the AC waveform, which generates a rotating magnetic field. This magnetic field interacts with the rotor, leading to mechanical motion. AC motors are prevalent in both household appliances and industrial machinery, thanks to the widespread availability of AC electrical energy.

There are two primary types of AC motors:

#### **Synchronous Motors:**

- ❑ Synchronous motors operate at a constant speed that is directly dependent on the frequency of the AC supply current.
- ❑ They are ideal for applications where consistency and precision are crucial, such as timing mechanisms or applications requiring a fixed speed.
- ❑ Synchronous motors may require external mechanisms or equipment to initiate rotation, especially when dealing with heavy loads, as they tend to start with relatively lower torque.
- ❑ These motors are most efficient when operating at their synchronous speed and may be less efficient at other speeds.

#### **Asynchronous Motors:**

- ❑ Asynchronous motors, also known as induction motors, do not operate at a constant speed but instead have a rotor speed that is always less than the synchronous speed.
- ❑ The speed of an asynchronous motor is influenced by the load it is driving, making them suitable for applications where speed variation is acceptable.
- ❑ They tend to start with higher torque, making them well-suited for applications with heavy loads, as they can generate significant torque when starting from a standstill.
- ❑ Asynchronous motors exhibit efficiency across a range of speeds and loads rather than being limited to a specific synchronous speed.

AC motors can be further categorized into single-phase and three-phase motors, depending on the electrical phase of the power supply they are designed to operate on. Residential electricity typically uses single-phase or double-phase power, necessitating the use of single-phase AC motors. In contrast, industrial settings often utilize three-phase power, requiring three-phase AC motors for various applications.

AC motors are equipped with various starters, including contactor starters and manual starters. Contactor starters enable the control of electrical power by using contactors to toggle power to the motor. Manual starters, on the other hand, allow the operator to directly switch or change the power supply, effectively wiring the motor directly to the power source.

There are several advantages to using AC motors:

- AC motors are known for their efficiency, as they can deliver good performance without overheating.
- They have a long lifespan, with small components that may need replacement only sparingly.
- When fixed speed is required, AC motors are preferred because the speed is directly controlled by the frequency of the AC power, offering precise control.

#### 3.1.6.1.2 DC MOTOR

A DC motor operates on Direct Current (DC) and is commonly powered by a battery or a DC power supply. One of the key advantages of DC motors is their ability to control speed by varying the supply voltage. This feature makes them suitable for applications where precise speed control is required or where simplicity in control is preferred. DC motors are widely used across various industries and applications.

A typical DC motor comprises two primary components: a stator and a rotor. The stator remains stationary and generates a magnetic field, while the rotor carries windings or permanent magnets. When an electric current is applied to the rotor, it interacts with the magnetic field generated by the stator, resulting in mechanical motion. This fundamental principle enables DC motors to convert electrical energy into mechanical motion efficiently.

DC motors offer distinct advantages, including higher starting torque without the need for as many external components as some other motor types. This characteristic makes them well-suited for applications where rapid acceleration or overcoming initial resistance is crucial.

There are three main types of DC motors:

##### Brushed DC Motor:

- Brushed DC motors feature brushes and a commutator, which are crucial for reversing the current direction in the rotor winding, causing the rotor to rotate.
- These motors are cost-effective in terms of initial purchase but may require more maintenance due to the possibility of brush wear over time.
- They find applications in various industries, including automotive systems and small appliances.

##### Brushless DC Motor (BLDC):

- Brushless DC motors use electronic controllers to switch the direction of current in the windings, creating a rotating magnetic field that drives the rotor.
- They are highly energy-efficient and reliable, with reduced maintenance requirements compared to brushed DC motors.



- BLDC motors are commonly used in robotics, electric vehicles, computer cooling fans, and other applications where efficiency and reliability are essential.

#### Coreless DC Motor:

- Coreless DC motors have rotor windings in a skewed or coiled shape and employ magnets embedded within the winding.
- They are known for their compact size and lightweight design, making them ideal for applications such as drones, medical devices, and other portable electronics.
- Coreless motors offer advantages in terms of reduced inertia and higher acceleration capabilities.

DC motors exhibit favorable speed and torque characteristics, often outperforming AC motors in these aspects. They are particularly well-suited for applications requiring variable torque or rapid acceleration. Additionally, DC motors generally require fewer adjustments to the power supply for operation, making them easier to integrate into various systems.

*Table 3.11 AC vs. DC Motor Comparison*

Criteria/ Motor Type	AC	DC
Power	Requires an inverter if powered by a DC source, less efficient more suited to be powered in an industrial or household setting	Requires constant voltage to remain powered, Generally more efficient, obtained from batteries usually.
Torque	More torque can be generated with use of a more powerful current	Faster responses to load changes <b>Brushed:</b> Higher starting torque <b>Brushless:</b> Constant RPMs <b>Coreless:</b> High torque in compact size
Motor Speed	Dependent on the frequency of an AC supply, variable frequency drives can be used, which allow for more control	Can be varied by adjusting the applied voltage or current, offer greater precision and efficiency in speed control compared to AC.
Cost Efficiency / Maintenance	Low cost, low maintenance, best cost efficiency in industrial setting	Generally, more than AC motors, best cost efficiency in small scale applications <b>Brushed:</b> Low cost, higher maintenance <b>Brushless:</b> Higher cost, less maintenance <b>Coreless:</b> Similar to brushless
Application	Better where power is needed for extended periods of time	Better where speeds need to be controlled externally

Control Complexity	Requires additional control systems to allow for precise control because of the need of frequency variation	Offers precise speed and position control, without need for additional control systems
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### 3.1.6.2 MODIFIED MOTORS

#### 3.1.6.2.1 SERVO MOTORS

A servo motor is a versatile type of motor designed for precise and controlled movements. It is commonly used for tasks that require pushing, pulling, lifting, or rotating at specific angles.

Servo motors are known for their exceptional accuracy, repeatability, and ability to provide smooth and continuous motion, making them a preferred choice in various industries, including robotics, automation, and 3D printing.

One of the defining features of servo motors is their ability to operate on either AC (Alternating Current) or DC (Direct Current) power. This versatility allows them to be adapted to different power sources and applications. Servo motors typically consist of several key components, including a gear assembly, controller, sensor, and feedback system.

The gear assembly plays a crucial role in increasing the torque output of the servo motor, making it capable of handling varying load conditions while maintaining precise control. The controller is responsible for processing input signals and generating the appropriate output to drive the motor.

Servo motors also incorporate sensors and feedback systems. These components provide critical information about the motor's position, speed, and torque output. By continuously monitoring and adjusting these parameters, servo motors can achieve high levels of precision and accuracy in positioning tasks.

One of the notable advantages of servo motors is their ability to adjust speed, torque, and position. This adaptability makes them suitable for a wide range of applications where dynamic and precise control is required. They can achieve speeds of thousands of RPMs, allowing for higher torque at useful speeds, making them ideal for tasks that demand both power and precision.

Servo motors often feature a variety of rotation arcs, but a common range is from 0 to 180 degrees. Typically, the motor starts at 90 degrees and can move 90 degrees in either direction. This flexibility in movement makes them versatile for applications with diverse motion requirements.

When utilizing servo motors, it's essential to consider the feedback system. The feedback system provides real-time information about the motor's position and performance. However, implementing a feedback system may require additional circuitry and control mechanisms to ensure accurate operation.

In terms of cost, servo motors generally have a higher initial cost compared to stepper motors due to their advanced control systems, feedback components, and precision capabilities.

However, they often have lower operating and maintenance costs over time, thanks to their efficiency, precision, and reduced wear and tear on mechanical components.

#### 3.1.6.2.2 LINEAR MOTOR

A linear motor is a specialized type of motor that offers linear motion by generating a magnetic field that moves along a straight line. Unlike rotary motors, such as stepper motors, which provide rotational motion, linear motors are designed to produce force and movement in a linear direction. They are typically powered by AC (Alternating Current) electrical energy, making them suitable for various applications that demand high-speed and high-precision linear motion.

One of the key advantages of linear motors is their ability to achieve high speeds and accelerations. This makes them well-suited for applications that require rapid and dynamic positioning, such as those found in the fields of automation, manufacturing, and transportation. In high-speed transportation systems, for example, linear motors are often used to propel vehicles at high speeds, offering an efficient means of transportation.

Linear motors are capable of providing substantial thrust and force in a linear direction. This ability to deliver high force makes them valuable in applications where powerful and precise linear movement is essential. Industries like semiconductor manufacturing and precision machining often rely on linear motors to drive the movement of critical components with accuracy and efficiency.

In comparison to other motor types, such as stepper motors, linear motors tend to be more expensive to acquire initially due to their specialized design and advanced capabilities. However, they can often operate at lower overall costs in the long run. Linear motors typically require less maintenance than traditional mechanical systems which have components which can wear out and need replacement over time. This reduced maintenance need not only saves on operational costs but also minimizes downtime and improves system reliability.

#### 3.1.6.2.3 STEPPER MOTOR

A stepper motor is a type of brushless DC motor designed to provide precise control over rotational movement. It operates by dividing a full rotation into discrete steps, with each step corresponding to a constant degree of movement. The motor achieves these steps by energizing poles in a specific sequence, ensuring controlled and incremental rotation. Stepper motors are widely used in applications where accuracy and repeatability are critical.

The operation of a stepper motor is governed by pulses of electrical energy. Each pulse corresponds to one step, allowing for precise control over the motor's position and rotation. Different stepper motors offer various step sizes, resulting in varying levels of precision. This makes stepper motors versatile for applications such as 3D printing, CNC machining, and robotics, where precise positioning and control are essential.

Stepper motors can also be found in various phases, and they can receive current in different manners. Two more common stepper motors are the 2-phase and the 5-phase stepper motors. The difference between these is how much the motor moves the teeth of the rotor, which affects the number of steps per revolution. These motors also be unipolar or bipolar, which is the manner in which they are receiving a current. For unipolar stepper motors, the current flows in the same

direction, therefore either the + or the – coil for a phase is powered, allowing for a simpler circuit because only a switch to alternate between the + and the – is needed. This also means half of the copper is used at once, so maximum torque cannot be reached. For a bipolar stepper motor, the current flows in both directions, for both the + and the – coil for the phase are powered, but the current can go from + to – or from – to +. A more complex circuit is needed to control this. Through doing this, all the copper is used, therefore maximum torque can be reached through this.

Unlike servo motors, which rely on a feedback system for precise positioning, stepper motors operate in an open-loop fashion. They respond to pulses without requiring feedback. However, there are limitations to this approach. For instance, stepper motors may struggle to advance the desired number of steps when encountering resistance or load variations. The motor must overcome friction and inertia to respond to each pulse accurately.

The speed of a stepper motor is controlled by the frequency of the pulses it receives. While stepper motors can provide precise control at low to moderate speeds, they may face limitations in high-speed applications. They tend to perform best below 1200 RPM. As the speed increases, the torque delivered by the motor decreases, which can impact their suitability for specific tasks.

Stepper motors are known for their ability to generate high holding torque, which is essential for maintaining the position of a load when the motor is stationary. However, their torque decreases as speed increases, which can influence their performance in dynamic applications.

Stepper motors are available in various frame sizes, with the NEMA 34 being one of the largest common sizes. This limits their maximum torque output to approximately 7 to 14 Nm, depending on the specific motor and design.

In terms of cost, stepper motors are often favored for their low initial cost, making them a cost-effective choice for many applications. However, they may require slightly higher operating costs due to their relatively lower energy efficiency compared to both servo and linear motors.

*Table 3.12 Motor Technology Comparison*

<b>Criteria/ Motor Type</b>	<b>Servo</b>	<b>Linear</b>	<b>Stepper</b>
<b>Power</b>	AC or DC, more often with DC, if AC is used, must be converted to controlled DC	AC or DC can be used, most dependent on application.	Typically, DC, more low-voltage DC applications, 12 or 24V
<b>Torque</b>	Can deliver high torque at low speeds, and maintain consistent torque across speeds, can also deliver peak torque for short durations	Because they produce linear motion, they provide thrust instead, but they can provide high force.	Delivers torque in discrete steps, which is constant up to a certain speed and have a high holding torque.

<b>Motor Speed</b>	Operate at both low and high rotational velocities, quick response to speed commands, require a feedback system to do so	Can achieve very high speeds with the speed controls being integrated into the control system, therefore speed and can be adjusted rapidly	Speed is related to the step rate, more limited speed range determined by design and frequency, at low speeds, they offer precise control
<b>Cost Efficiency / Maintenance</b>	Higher initial cost, low operating, and maintenance cost	High initial cost, also lower operating and maintenance cost	Most affordable initial cost, can require more maintenance over time, slightly less energy-efficient
<b>Control Complexity</b>	Require advanced control systems for position and speed control, commonly an encoder	Can require complex control systems including sensors and feedback loops but depends on application	Receive step commands without requiring an encoder
<b>Accuracy / Precision</b>	Precise and accurate, allow for high repeatability and tolerance control	Can have high accuracy and precision, ideal for fine positioning requirements	Precise in discrete steps, can have limited accuracy at times

### 3.1.7 MOTOR CONTROLLER

All motors will require some controller or driver to provide power and potentially control the voltage and direction of the motor is that is a possibility with that particular motor type. The technology used for the motor controller is reliant on the type of motor selected.

For an AC or DC motor, the controller can be as simple as a motor starter or a direct power connection. These starters also typically have protection against electrical and mechanical overload. They can either provide voltage to the motor directly or be a reduced voltage starter which supplies the voltage to the motor gradually. An AC motor can have an AC motor driver which is able to control the speed, which would have to adjust the frequency to be able to do this. For brushed DC motors, the speed can be controlled through varying the voltage, so along with the starter, a device to be able to vary the voltage is required, but still doesn't require a dedicated controller. For a brushless DC motors, the motor is controlled based on the magnetic field it experiences, so a controller is needed to be able to adjust this field.

Servo, linear, and stepper motors require a controller because commands must be sent to a control system to allow for movement of the motor in a desired manner. Linear motors still rely on DC drives, whereas servo and stepper motors rely on their own respective drives.

Servo motors rely on a servo drive that allows for them to output desired movements. These drivers rely on pulse width modulation of the input to control the motor. These allows for control of the position, torque, and motor speed.

Stepper motors rely on a stepper drive, which modifies the input current to be sent as a pulsed output, which allows for providing the steps to the motors. These, similar to servo motors, allow for control of the position, torque, and motor speed.

### 3.1.8 ANTENNA

For the rover's effective operation, its antenna requires specific characteristics. Directivity, gain, polarization, beamwidth, center frequency, and efficiency are crucial qualities to consider when selecting the antenna.

In the case of the rover, extremely high directivity is not necessary since its position varies depending on the tower. Therefore, the antenna must be able to receive and transmit signals omnidirectionally, accommodating both downlink and uplink communication. The gain follows the same principle but considers potential losses. For the rover's application, it's essential to account for signal degradation during transmission.

Due to potential changes in the orientation of the antennas relative to each other, polarization mismatch can be a concern with linearly polarized antennas. For this reason, circularly polarized antennas are more suitable, as they are more robust against polarization mismatch, making them ideal for scenarios where the orientation of the rover's antennas can vary during movement. Circularly polarized signals maintain their polarization characteristics regardless of the receiving antenna's orientation, ensuring reliable communication for a non-stationary rover. Although circular polarization may introduce some additional complexity and suffer slightly more losses, it is the best choice for this application.

Wider beamwidth enhances coverage and ensures continuous communication between the tower and the rover, even when the exact position is unknown. Additionally, a wider beamwidth reduces complexity, as narrow beamwidths would require constant tracking mechanisms to maintain a strong link.

The center frequency of the rover's antenna should be 2400 MHz, aligning with the frequency used for communication with the tower.

Lastly, efficiency is a critical quality. The rover must be capable of operating for extended periods without recharging. An efficient antenna is essential to conserve power, as any wastage could impact the rover's overall performance, even if it's only a tiny amount.

*Table 3.13 Antenna Technology Comparison*

	Dipole	Patch	Reflector (Parabolic)	Yagi – Uda	Helical Antenna	Aperture (Horn)
Gain (dBi)	1.76-7	0.5 -10	10 - 40	5 – 20	3 – 15	10 – 25
Polarization	Linear	Linear/ Circular	Circular	Linear	Circular	Linear/ Circular
Efficiency	High	High	High	High	High	Very High
Bandwidth	Narrowband	Wideband	Narrowband	Narrowband	Wideband	Narrowband

Directivity	Omni - directional	Omni - directional	Highly Directional	Highly Directional	Directional	Highly Directional
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#### 3.1.8.1 SHORT DIPOLE ( $L < \lambda/10$ )

There are multiple versions of the dipole antenna, each with essential characteristics. The short dipole provides less than 1.76 dB directivity in an omnidirectional pattern [Peter Joseph Bevelacqua]. The beam width is also relatively wide. Although an antenna with these specifications is desirable, it is essential to note that its omnidirectional characteristics decrease as directionality increases. In most cases, three dBi of directivity is sufficient for an antenna to qualify as omnidirectional.

Another issue is that the antenna is linearly polarized, which could cause problems when the rover moves. Additionally, matching a short dipole antenna is difficult because of its considerable reactance value when calculating the load impedance; this can result in efficiency issues due to the high VSWR (Voltage Standing Wave Ratio). Moreover, considering the importance of reactance is so high, implementing a matching network would be challenging, resulting in a narrow-band design to maintain signal quality and avoid losses.

Therefore, for this project's purposes, the short dipole antenna is not the best choice as it is linearly polarized and would result in low efficiency. Exploring other antenna options with higher directivity and better polarization characteristics would be more suitable for achieving the project's goals and ensuring reliable signal transmission.

#### 3.1.8.2 DIPOLES

The dipole antenna exhibits varying directivity depending on its lengths, namely  $\lambda/4$ ,  $\lambda/2$ , and  $\lambda$ . As the antenna's length approaches 1.25 times its wavelength, the directivity experiences an exponential increase. However, for longer distances beyond this point, the directivity continues to increase, but not in a strictly monotonic manner. At such lengths, the directivity surpasses 1.76 dB and can reach approximately 5.2 dB. This substantial increase in directivity compared to the short dipole antenna allows for more excellent energy directionality. This directivity doesn't necessarily make it more suitable for the rover application, as it can potentially direct more energy.

Unfortunately, the antenna remains linearly polarized, which may not be ideal for the rover's specific communication requirements. The reactive impedance was high and capacitive for the short dipole, but the half-wave dipole (slightly under  $0.5\lambda$ ) has a reactive impedance component of 0, indicating resonance. This leads to greater radiated power by the antenna (low S11 at the resonant frequency) and significantly simplifies the design of the impedance-matching network, resulting in improved efficiency since only actual impedances need to be transformed.

Considering these factors, the optimal length for the dipole antenna in this project is the half-wavelength dipole. It offers a satisfactory level of gain and superior efficiency. However, it's important to note that the linear polarization of this antenna may pose challenges when communicating to and from the tower—the half-wavelength dipole balances directivity and efficiency for the rover's intended use.

### 3.1.8.3 PATCH

Patch antennas, or patch antennas, have a practical design because they can print directly onto a printed circuit board (PCB). They maintain a low-profile form factor, ensuring easy fabrication and simple integration into size-constrained designs. Most antennas exhibit an average of 5-7 dB of gain, with a tendency towards 5 dB, a reasonable value for the present project's requirements [Peter Joseph Bevelacqua].

As for the polarization, patch antennas are flexible. They can exhibit different polarizations based on the location of the feed(s) lines [Breed]. The latter is best for this project. Although they predominantly feature a narrowband characteristic—generally manifesting a bandwidth approximating 3%—their utility remains intact [Peter Joseph Bevelacqua]. Originally architected to operate at frequencies as low as 100 MHz, contemporary variants are adept at functioning at elevated frequencies, including the 2400 MHz operational frequency utilized for the mesh network in this instance.

Conventional patch antennas typically have a beamwidth of about 65 degrees [Breed]. Additionally, they commonly feature a commendably high efficiency, predominantly situated within the 80-90% bracket.

### 3.1.8.4 PARABOLIC REFLECTOR

Parabolic reflector antennas, also known as satellite dish antennas, are known for their substantial gain, typically within the 30-40 dB range, surpassing 50 dB in some instances [Peter Joseph Bevelacqua]. Moreover, they boast a considerable bandwidth, a characteristic influenced by the dimensions of the dish. While standard commercial models commonly possess a 5% bandwidth, extensive dishes can achieve wideband levels. Large variants can operate across a spectrum from 150 MHz to 1500 MHz. In contrast, smaller dishes generally function within the 2000 to 28000 MHz band. The efficiency of parabolic reflectors is around 50-70%, which is acceptable for the project requirements.

The polarization of this antenna can assume multiple forms, contingent upon the feed antenna incorporated in the design. Therefore, the antenna can be circularly polarized to accommodate project requisites.

The parabolic reflector's best quality is its directivity. By utilizing the dish (the reflector), the directivity of a parabolic reflector antenna is characteristically high. The antenna can achieve directivities in the 30-40 dB range. Within the context of the rover network, excessive directivity—surpassing 5 dB—risks being harmful, while a more expansive beamwidth is desirable.

### 3.1.8.5 YAGI-UDA

The Yagi-Uda antennas have high gain with a small bandwidth. The frequency range within which Yagi-Uda antennas operate, HF to UHF, resonates with the project requirements.

The configurational attributes of the Yagi-Uda antenna—such as the number of elements, their respective lengths, and their spacing—are important factors influencing its performance characteristics, thus providing flexibility should this antenna type be selected. A notable advantage embedded within the Yagi-Uda antenna is its elevated gain, consistently surpassing 10 dB. The antenna can achieve gains exceeding 16 dB by optimizing the spacing between director



elements, with an upper limit proximate to 20 dB. Notably, within the Yagi-Uda antenna, an inverse proportionality relationship is observed between gain and beamwidth.

The Yagi-Uda antenna generally exhibits a narrower beamwidth than alternative antenna types. Given the project's prerequisite for a broad network with mobile devices, this presents a substantial drawback. Furthermore, the Yagi-Uda antennas are linear polarized, either horizontal or vertical, which, given the network functionality demands of the project, recommending circular polarization, constitutes a significant limitation. The gain of the Yagi-Uda antenna typically resides in the 7-9 dB range, a metric higher than desirable for the rover network. Yagi-Uda antennas with elevated gain can achieve efficiencies of around 75%, a reasonable value for the rover application.

#### 3.1.8.6 HELICAL

A helical antenna with specific design parameters can be advantageous for communicating between a tower and a rover. Shorter helical antennas with fewer turns and a larger pitch tend to have lower directivity, making them more suitable for maintaining an omnidirectional radiation pattern. This benefits the rover as it allows for continuous communication regardless of its orientation.

Another advantage of helical antennas is their polarization diversity. By adjusting the orientation of the helix, the antenna can be either right-hand circularly polarized (RHCP) or left-hand circularly polarized (LHCP). This feature helps mitigate the effects of polarization mismatch and signal fading during communication between the tower and the rover.

However, one limitation of helical antennas is their narrower bandwidth than other antenna types. Proper tuning and impedance matching are crucial to achieving optimal performance and efficiency across the desired frequency range. On the bright side, the helical antenna's input impedance is primarily actual, making impedance matching easier and potentially resulting in higher efficiency, even though some loss may still occur.

For the rover's applications, a smaller helical antenna could be a suitable choice as it provides an appropriate level of directivity, offers circular polarization, and can optimize efficiency for effective communication with the tower.

#### 3.1.8.7 HORN

Horn antennas offer high directivity, enabling focused signal transmission and reception to and from the tower. However, striking a balance with the antenna's directivity is essential for a mobile rover that requires omnidirectional coverage while moving. It should provide enough focus toward the tower while maintaining a relatively wide coverage area around the rover.

A circularly polarized horn antenna is advantageous for a rover that changes orientation while moving. Circular polarization ensures stable signal transmission, maintaining reliable communication with the tower, regardless of the rover's position or rotation.

Efficiency is highly beneficial for a rover's communication system. Horn antennas are known for their excellent power radiation efficiency, efficiently converting input power into radiated electromagnetic energy. This efficiency is especially valuable for battery-operated rovers, conserving power, and extending operational periods and communication sessions with the tower.

Therefore, the horn antenna's directivity, polarization, and efficiency significantly impact the rover's communication capabilities with the tower. An optimized horn antenna, balanced directivity, circular polarization, and high efficiency ensure a stable and reliable communication link, allowing seamless connectivity as the rover moves and interacts with the tower. However, balancing all the parameters can be particularly challenging for the horn antenna.

#### 3.1.8.8 ANTENNA CHOICE

Of the antennas researched for this project, the helical and patch antennas are the most suitable. These two options stand out due to the challenging task of finding an antenna that meets most of the project's specifications.

With its moderate directivity, the patch antenna can provide an omnidirectional radiation pattern. This characteristic is essential for our application, where the rover's position relative to the stationary tower could change. Similarly, although generally known for its higher directivity, the helical antenna can achieve a quasi-omnidirectional radiation pattern when its size, number of turns, and pitch is correctly adjusted.

One area where the helical antenna bests the patch antenna is polarization. While patch antennas can achieve circular polarization, they are less commonly designed for this mode of operation. Conversely, helical antennas are inherently circularly polarized, aligning better with our desired antenna operation. Unfortunately, it's hard to find patch antennas that radiate a circularly polarized field.

In terms of efficiency, both the patch and helical antennas are great. A patch antenna's impedance is mostly actual when appropriately designed, which simplifies the task of efficient power transfer. Similarly, helical antennas have a dominant real impedance component, facilitating efficient power conversion from electrical current to electromagnetic waves.

The patch antenna's primary advantage over the helical antenna is its form factor. Due to their planar design, patch antenna's topology is slim, making them more compact and suitable for space-constrained applications. Although helical antennas can be miniaturized, they will inevitably occupy more space than the patch antenna.

The antenna choice must be optimal, as finding one that meets all the specifications mentioned is tricky.

#### 3.1.9 COMMUNICATION PROTOCOLS

##### 3.1.9.1 6LoWPAN

6LoWPAN (IPv6 over Low-Power Wireless Personal Area Networks) supports IEEE 802.15.4 low-power wireless networks, primarily operating in the 2.4 GHz band but also supporting sub-GHz bands such as 868 MHz in Europe and 915 MHz in North America. This adaptation aims to optimize the transmission of IPv6 packets over low-power and low-throughput networks. With a typical throughput ranging from 20 kbps to 250 kbps, depending on the specific frequency band and modulation scheme, 6LoWPAN enables efficient encapsulation and header compression mechanisms that allow the larger IPv6 packets to operate networks with significant constraints.

The low power requirements, typically 1-100 mW depending on the implementation and operational mode, make it particularly suitable for battery-operated devices. 6LoWPAN has many advantages for establishing a mesh network for IoT devices, as it can deliver low-cost and

secure communications. Its interoperability with standard IP networks extends its applicability to a wide range of devices, from small sensors to smartphones.

The scalability and flexibility of 6LoWPAN facilitate its integration into various application scenarios like home automation, industrial monitoring, and health care. It further contributes to energy efficiency by handling sleep-and-wake cycles effectively, extending the operational lifespan of battery-powered devices. Moreover, 6LoWPAN includes robust security provisions, such as end-to-end encryption, to ensure secure connections.

Overall, 6LoWPAN represents a vital advancement in wireless networking, meeting the specific requirements of emerging IoT applications and other low-power, low-bandwidth networking environments, making it a preferred choice for many developers and organizations.

### 3.1.9.2 BLUETOOTH

Bluetooth is a wireless technology standard for exchanging data between fixed and mobile devices over short distances. It operates in the 2.4 GHz band, allowing for global compatibility across devices and regions. Bluetooth's architecture is designed for low power consumption, with power levels varying between 1 mW and 100 mW, making it suitable for battery-operated gadgets like smartphones, headphones, and wearables. Data rates can range from 125 kbps to 2 Mbps in classic Bluetooth and up to 50 Mbps in Bluetooth 5, enabling seamless communication for various applications. The network topology of Bluetooth can be point-to-point or point-to-multipoint, accommodating different connectivity needs. Its robust frequency-hopping spread spectrum technique enhances resistance to interference and security. Additionally, Bluetooth incorporates various security mechanisms, including authentication and encryption, to ensure the integrity and confidentiality of data. Bluetooth technology continues to evolve, with newer versions offering increased range, speed, and functionality.

### 3.1.9.3 LORAWAN

LoRaWAN (Low Range Wide Area Network) is a media access control (MAC) protocol for wide area networks that supports long-range, low-power devices. It operates in various license-free bands globally, such as 868 MHz in Europe and 915 MHz in North America, allowing for broad adoption across different regions. LoRaWAN's architecture is optimized for low-power consumption, typically between 10-50 mW, depending on the device's configuration and usage, making it highly suitable for battery-operated IoT applications. Data rates ranging from 0.3 kbps to 50 kbps, depending on the spreading factor and bandwidth, enable efficient data transmission over distances exceeding 10 kilometers in rural areas. The network topology of LoRaWAN can be set up in a star or mesh configuration, facilitating flexible connectivity for various applications, including smart cities, agriculture, and asset tracking. The inherent robustness of LoRa's modulation technique allows for strong signal penetration and resilience to interference.

Furthermore, LoRaWAN classifies devices into three primary categories: Class A, Class B, and Class C, based on their communication patterns and energy consumption. Class A devices are the most energy-efficient, opening receive windows only after an uplink, ideal for intermittent data transfer in applications like environmental monitoring. Class B devices have scheduled receive slots for more frequent downlink communications, suitable for utility metering or firmware updates, without significantly increasing power consumption. Class C devices, with almost continuous receive windows, offer the lowest latency and are best for near-real-time applications such as street lighting control or industrial automation, though they consume more power. LoRaWAN's scalability supports large-scale deployments, and its encryption mechanisms (using

AES-128 encryption) provide end-to-end security, ensuring data integrity and confidentiality. The protocol also includes adaptive data rate management features, maximizing energy efficiency and network capacity. LoRaWAN can connect sensors and devices in remote or challenging environments where traditional cellular or Wi-Fi networks may not be viable. Overall, LoRaWAN represents a significant innovation in wireless networking, providing a versatile and efficient solution to meet the needs of various low-power, wide-area applications.

#### 3.1.9.4 Wi-Fi

Wi-Fi 6 is adaptable to the 2.4 GHz and 5 GHz bands. In ideal conditions, using two spatial streams and 1024-QAM modulation, it can reach speeds up to 2.4 Gbps, making it the fastest protocol in this discussion. Yet, it has limitations. Its maximum range is roughly 45 meters, with a high-power consumption of around 250 mA, which isn't ideal for battery-operated devices. Furthermore, while fast, the 5 GHz frequency struggles to penetrate solid objects, limiting its effective range.

Globally recognized, Wi-Fi seamlessly integrates with various devices, addressing multiple requirements. However, its use of the saturated 2.4 and 5 GHz bands often makes it prone to signal disruptions.

#### 3.1.9.5 ZIGBEE

Rooted in the IEEE 802.15.4 standard, Zigbee stands out as a flexible wireless communication platform, ideal for applications that prioritize power efficiency and consistent short to medium-range data transmission. ZigBee's low throughput rate, reaching a maximum of 250 kbps in the globally accessible 2.4 GHz band, comes with a distinct advantage: it allows the system to have a peak current consumption of just 54 mA. This efficiency is particularly beneficial for tasks that demand economic power usage, making it a favored choice for battery-operated sensors in smart homes, agricultural environments, and industrial IoT setups.

A hallmark of Zigbee is its support for mesh networking. In such a configuration, individual devices, known as "nodes," can forward data on behalf of other nodes. Hence, if a device isn't in direct communication range, it can still contribute and benefit from the more extensive network, making Zigbee resilient in areas where physical barriers or distance could disrupt direct signal paths.

In addition to its operational efficiency, Zigbee gives considerable weight to security. The protocol inherently employs encryption and authentication tactics grounded in the AES-128 standard. This standard ensures that data remains shielded from unwanted interceptions and unauthorized intrusions.

Zigbee has multiple issues. Operating within the 2.4 GHz band means it contends for space with other wireless technologies, such as Wi-Fi and Bluetooth. This cohabitation can lead to potential interference and network congestion. However, strategies like adaptive channel hopping offer a level of mitigation against these interference-related challenges.

#### 3.1.9.6 Z-WAVE

Z-Wave is a unique low-bandwidth wireless protocol tailored for dependable, budget-friendly control networks. While Z-Wave devices can transmit data at speeds of 40 kbps and use only one mW of power, they can reach speeds up to 100 kbps. However, these speeds are less robust than protocols like ZigBee. Hence, Z-Wave is less suited for applications requiring high data transfers

or precise timing. Furthermore, its indoor range is at most 50 meters which is a limitation. Z-Wave can relay messages between nodes, effectively broadening its functional range. A standout feature of Z-Wave is that it operates on a frequency distinct from the 2.4 GHz used by Wi-Fi and Bluetooth, minimizing potential interference with devices on those protocols. Since Z-Wave is a proprietary system, it's primarily compatible with devices built specifically for it. Its operating frequency varies by country, ranging from 865.20 to 921.40 MHz. Therefore, products must share the same frequency to be interoperable, and designs may need adjustments if intended for multi-region deployments.

#### 3.1.9.7 CHOICE FOR COMMUNICATION PROTOCOL

Zigbee is a great choice for a communication protocol, especially in implementing a mesh network on the moon, which demands efficiency and flexibility. Principal among Zigbee's advantages is its energy efficiency, which is important in ensuring battery life of devices in a setting where consistent power generation and recharging are not guaranteed. Furthermore, Zigbee devices are renowned for their capability to create and host mesh networks where every device acts as a passive node and a proactive contributor, routing and extending the network. This methodology ensures that the network remains resilient; if one node fails or encounters issues, the network dynamically reconfigures, maintaining communication integrity by utilizing alternative pathways. Scalability is another benefit, Zigbee can assimilate additional devices, amplifying the network's breadth and robustness. This trait could prove invaluable, providing a flexible framework for potential lunar explorations. While Zigbee may not offer the highest data throughput, its resilience, and low-bandwidth utilization make it suited for the moon, where stability and reliability outweigh the need for speed, ensuring that crucial real-time communication and data transfer between lunar modules, rovers, and other technological apparatus remain uninterrupted.

#### 3.1.10 CHARGING STATION

One of the goals of this project is to build a charging station. The main purpose of this station is for the operator to have the ability to drive the rover in the station and start charging without the need for a human to plug the battery in. This would facilitate the recharging process through remote charging. On the moon, this characteristic is important since the astronauts have a suit that may make it difficult to handle a charging port. There are two main ideas that can enable remote charging in this application.

The first choice would be to use supercapacitors so that the rover can be charged wirelessly. This would make charging relatively slow and inefficient. As discussed previously under the supercapacitor section, this will be considered a stretch goal for this project. This decision was made since the first version of this power station must be reliable and within budget. In the future, this solution may be used for easier connection.

The second choice is to design a mechanism that allows the rover to be driven into the charging port. This would require the correct positioning of the charging port in both y and x axis. For the x axis, the trails on the ground would serve as the guide so that the rover is driven in the right direction. For the y axis, the charging port will be positioned and fixed at the correct level so that when the rover drives in, the port is at a good level.

For this project, the second choice is much more feasible. The battery port and charging method will be crucial for this solution to work. This will be taken into consideration when choosing the battery, since the shape and method of charging will affect the design of the station.

### 3.1.11 CONTROLLER APPLICATION

The application controller for the rover will be built on top of Florida Space Institute's pre-existing code base that has a mobile application built for wirelessly communicating, through the 802.11 standard, motor control instructions to the rover.

The application that this project will be building functionality on top of is the EZRASSOR-CART application. It is written in JavaScript and works on the Node.js framework. In order to interface with the rover, both the rover and the device using the mobile application must be on the same local area network which is done through Wi-Fi. Currently, this application is deployed on a Linux-like operating system. Therefore, in order to effectively build on top of this framework as desired, the selected microcontroller for this project must be able to run a Linux-based operating system.

Underlying the EZRASSOR-CART controller application is the EZRASSOR\_controller repository which contains the basic API for the web service that the application uses as the transmission channel for communication motor control commands, building the UI for the mobile application's rover motor control, defining the several motor control command enumerations to be used in development. The communication system between the mobile application, Potato Pi microcontroller and the Arduino uses a framework called ROS2, which is a software library built for developing robot applications. Previous and ongoing projects at the Florida Space Institute use this framework for communicating motor controls between the input source and to and through the microcontrollers.

## 3.2 CORE COMPONENTS AND PARTS SELECTION

### 3.2.1 MCU

Since the rover system must be capable of video processing and mesh networking, two separate microcontrollers will be selected to each best support the aforementioned applications. The ESP32-C6-WROOM microcontroller serves as the best candidate for developing a mesh network application due to its versatile wireless capabilities, such as IEEE 802.11ax Wi-Fi compliancy, Bluetooth LE and Bluetooth mesh, and the Thread 1.3 and Zigbee 3.0 standards. In addition to its built-in wireless capabilities, it also supports external antennas through the I-PEX connector. Its low power RISC-V processor also provides an advantage in saving power where possible given that the rover will be battery-powered and therefore, power-savings are pertinent to the performance of the product. However, where performance is crucial, the microprocessor does have a high-performance processor to meet those needs. Where the ESP32 falls short for the needs of this project is its lack of a CSI-2 connector for a camera module. However, this is where the Raspberry Pi Zero 2 W steps in. The Raspberry Pi Zero 2 W does feature a CSI-2 camera connector, allowing for high resolution, high frame rate video capture from a camera module. The board also supports H.264 video encoding which is capable of encoding up to 1080p30 video. While the H.264 standard is very demanding on the CPU, the Pi Zero 2 W should provide plenty of performance headroom.

Despite these justifications, the ESP32 and Raspberry Pi Zero 2 W do not meet the needs of the project sponsor. The pre-existing rover project that this project is building on top of has a pre-established mounting system for the micro-computing electronics that our team must adhere to. In addition, the RAMPS 1.4 board which is used to provide additional power to the motor controllers is designed especially for the Arduino Mega form factor. These constraints translate into deferring the choice of the ESP32 and Raspberry Pi Zero 2 W in favor of the Le Potato Mini for fulfilling the camera processing and wireless communication needs of the project and the Arduino Mega 2560 for processing and sending instructions to the motor controllers. The Le Potato Mini has the advantage of being an existing microcontroller that previous projects have developed on. This means that there is pre-existing software that can be adapted to be used for the purposes of this project. One major concern in this decision is that the Le Potato Mini does not natively support the Zigbee communication standard to be used in the mesh networking system of the project.

### 3.2.2 CAMERA TECHNOLOGY SELECTION

SPI has the lowest bandwidth of all the camera technologies with a mere 60 Mbps. Therefore, the interface will not be sufficient for the needs of the project because the goal is to implement video streaming from the microcontroller to the app controller with at least 30 frames per second video. GMSL is not a suitable interface either because of its high costs compared to the other technologies and its support cable length is much longer than what is needed for this project. Now, this leaves the CSI-2 interface and the USB interface. The CSI-2 interface supports a much higher bandwidth compared to USB, but the USB interface supports cable lengths (5m max.) much longer than the CSI-2 interface (30 cm max.) Since the rover being built is going to be relatively small, the tradeoff of the CSI-2 interface's 30 cm maximum cable length will not be as much of a limiting factor compared to the lower bandwidth of USB. However, the video stream used for the purposes of this project will not require the maximum theoretical bandwidth offered by the CSI-2 interface. One further aspect to consider is the fragility of the connections for the CSI-2 and the USB interfaces. The CSI-2 interface uses a small ribbon cable that has a small latch on the connection to hold the ribbon in place. Both ends of the connection usually have this latch. However, the latch is still quite fragile and can be easily broken if too much tension is applied on the ribbon cable. A USB cable provides a much more physically resilient connection. Having a relatively large (compared to CSI) connector fit into a metal port will be a much more rigid connection compared to the fragile ribbon cable and latch. Given that the rover will be moving quickly through uneven terrain and in theory, in a low gravity environment, the physical integrity of all components is pertinent to a durable product.

With all these aspects considered, the USB interface proves to be the best suited interface for the purposes of this project with a good trade between maximum bandwidth and cable length and physical integrity.

*Table 3.14 Communication Interface Comparison*

<b>Interface</b>	<b>SPI</b>	<b>USB 3.0</b>	<b>GMSL</b>	<b>MIPI CSI-2</b>
<b>Max. Bandwidth</b>	60 Mbps	5 Gbps	6 Gbps	16 Gbps

<b>Max. cable length</b>	10 meters	5 meters	15 meters	30 cm
<b>Connection Type</b>	4 wires	USB connector	GMSL cable	Flex cable
<b>Space Requirement</b>	Low	High	High	Low
<b>Cost</b>	\$26-40	\$35-64	\$300-400	\$20-120

### 3.2.3 CAMERA COMPARISON AND SELECTION

*Table 3.15 Candidate Camera Module Comparison*

<b>Camera</b>	<b>Arducam IMX708 B0310</b>	<b>Arducam IMX708 B0309</b>	<b>Raspberry Pi Camera Module V3</b>	<b>Arducam B0161</b>
<b>Sensor</b>	Sony IMX708	Sony IMX708	Sony IMX708	OmniVision OV7251
<b>Color</b>	Yes	Yes	Yes	No
<b>Still Resolution</b>	11.9 MP	11.9 MP	11.9 MP	0.3 MP
<b>Sensor Resolution</b>	4608 x 2592 pixels	4608 x 2592 pixels	4608 x 2592 pixels	640 x 480 pixels
<b>Video Modes</b>	2304×1296p56, 2304×1296p30 HDR, 1536×864p120	2304×1296p56, 2304×1296p30 HDR, 1536×864p120	2304×1296p56, 2304×1296p30 HDR, 1536×864p120	640x480p30
<b>Shutter Type</b>	Rolling	Rolling	Rolling	Global
<b>Focus Type</b>	Manual	Fixed	Motorized	Fixed
<b>Focal Length</b>	2.87 mm	2.75 mm	4.74 mm	1.3 mm
<b>Field of View (FOV)</b>	120°	102°	66°	72.9°
<b>Camera Board Size</b>	25mm x 24mm	25mm x 24mm	25mm x 24mm	24mm x 25mm
<b>Price</b>	\$36.99	\$29.99	\$45.99	\$35

<b>Camera</b>	<b>Arducam B0224</b>	<b>Arducam B0393</b>	<b>Arducam Octoprint Octopi B0176</b>	<b>Arducam IMX 708</b>
<b>Sensor</b>	OmniVision OV9281	IMX219	OmniVision OV5647	Sony IMX708



<b>Color</b>	No	Yes	Yes	Yes
<b>Still Resolution</b>	1 MP	8 MP	5 MP	12 MP
<b>Sensor Resolution</b>	1280 x 800 pixels	3280 x 2464 pixels	2592 x 1944 pixels	4608x2592 pixels
<b>Video Modes</b>	1280x800p120	1080p47,1640x1232p41 640x480p206	1080p30, 720p60, 480p90	4608x2592@10fps,2304x1296/ 1080p/1200p/720p@30fps
<b>Shutter Type</b>	Global	Rolling	Global / Rolling	Rolling
<b>Focus Type</b>	Manual	Programmable/ Auto Focus	Motorized	Fixed Focus
<b>Focal Length</b>	N/A	2.8 mm	N/A	N/A
<b>Field of View (FOV)</b>	110°	65°	54°	66°
<b>Camera Board Size</b>	40mm x 40mm	25mm x 24mm	25mm x 24mm	25mm x 24mm
<b>Price</b>	\$57	\$26	\$20	\$49.99

The table above lists various CSI-2 cameras that could potentially be suitable for the purposes of this project. The Arducam IMX708 B0309 and B310 both share the same image sensor but have different lens technologies. The B310 has a rolling shutter with a 120° FOV manual focus lens. The B0309 also has a rolling shutter while having a 102° FOV fixed focus lens. These two cameras support up to 2304x1296p56 video capture and have a 11.9-megapixel sensor. Each of these cameras while being beneficial in their wide field of view lenses, the lack of autofocus capability is a disadvantage given that the rover that the camera will be mounted on will be in motion within a dynamic environment. Therefore, having autofocus is essential to maintaining clear video footage for the operator. Although being more budget-friendly, the Arducam B0161 and B0224 are also ruled out due to a need for autofocus capabilities on the camera. This leaves the Raspberry Pi Camera Module v3, Arducam B0393, and the Octoprint Octopi. The Raspberry Pi CM v3 and the Octoprint Octopi Camera Module features a motorized focus lens which essentially boils down to the fact that the module has autofocus capabilities. Similarly, the Arducam B0393 camera module has a programmable lens, allowing for autofocus capabilities as well. What sets the Raspberry Pi Camera Module v3 apart from the other two similarly specified offerings is the support for the open source libcamera library for Linux, Android and Chrome OS and the Picamera2 library, making interfacing and developing an application for the camera much more straightforward. With that said, it is clear that the the Raspberry Pi Camera Module v3 offers the best solution for the needs of the project having autofocus capabilities, pre-existing software interfaces, and being beyond capable of capturing at least 480p60 video. The only setback presented by this component selection is that the shutter type of the Raspberry Pi Camera Module v3 is rolling instead of global, which means that motion blur in images become more prevalent. However, the benefits of this camera module far outweigh its undesirable aspects.

Due to physical constraints of the rover, the CSI-2 connector proves to be too fragile of a connection to be used reliably in this project. However, CSI-2 cameras can still be used given that a CSI-2 to USB UVC adapter board is available for that sensor.

The Arducam IMX708 USB Camera Module 3 represents a suitable option for the purposes of this project. It uses a CSI-2 camera sensor but comes with a CSI-2 to USB UVC adapter board pre-installed. Purchasing a separate adapter board alongside our previous decision on the Raspberry Pi Camera Module v3 is another option for implementation. However, at this time, it is more cost-effective to purchase an all-in-one solution as in the Arducam IMX708.

### 3.2.4 BATTERY

The current setup is powered by a 12 Volt 9Ah battery. One of the main requirements for this project in terms of power is to increase the power supplied to the rover and supplying 24V to the rover, which will be done by choosing a new battery. The battery will provide power to the MCUs, as well as the motor controllers. There will be regulator circuits between each of those connections to ensure the correct voltage is being delivered. For some of the devices, the operating voltage may be less than the battery voltage. In this case, there will be a step-down regulator circuit to ensure the devices are getting the appropriate operating voltage.

The battery will be rechargeable. The method used to recharge the battery is relevant to this project. Since it is desired that the battery is recharged without human contact, it would be ideal to have a system to provide this. Since this is considered a stretch goal for this project, this will be taken into consideration but not as a requirement.

To increase the power delivered, the rover can be powered by a 24V power battery with the same Ah as the existing battery. Another way to achieve 24 Volts is to use two 12V batteries in series. For this project, both options will be considered. Using 12V batteries may be advantageous considering they are much more widely available than the other option. Also, if there was a failure with one of the batteries, the system can be adapted to operate using only one of the batteries without requiring an immediate spare battery. This can be particularly important when the rover is on the moon, since not many replacement parts will be available. It would also be cheaper to replace one 12-volt battery than a 24-volt battery. However, there may be an issue with physical space. Two 12-volt batteries will likely take up more space than one 24-volt battery. This new system may not fit the current design for the electronics compartment. The solution to this would be to redesign this compartment. One of the disadvantages of this system would be the increased complexity. Handling two batteries is more work than handling one. This complexity could add more failures to the project as well as more maintenance to the rover.

*Table 3.16 Candidate Battery Comparison for Series Implementation*

<b>Battery</b>	<b>Eco-Worthy</b>	<b>NERMAK</b>	<b>Feuruetc</b>
<b>Voltage</b>	12	12.8	12
<b>Ah</b>	10	10	6
<b>Chemistry</b>	LiFePO4	LiFePO4	LiFePO4

<b>Dimension</b>	5.9 * 2.56 * 3.7 inches	5.94 x 2.56 x 3.7 inches	3.54 x 2.75 x 3.93 inches
<b>Weight</b>	2.46 lbs	2.64 lbs	3.27 lbs
<b>Cycles</b>	3000+	2000+	2000+
<b>Price</b>	\$80.98	\$79.99	\$39.50
<b>Number of batteries</b>	2	2	2
<b>Total price</b>	\$80.98	\$79.99	\$39.50

There is a third way of meeting the requirement of increasing the power supply. That would be to keep the voltage the same but double the Ah, meaning 12 Volts and about 18Ah. Below is a table for some batteries that meet those requirements.

*Table 3.17 Candidate Battery Comparison for Double Current Implementation*

<b>Battery</b>	<b>XZNY</b>	<b>NERMAK</b>	<b>CHINS</b>
<b>Voltage</b>	12	12	12
<b>Ah</b>	18	18	20
<b>Chemistry</b>	LiFePO4	LiFePO4	LiFePO4
<b>Dimension</b>	5.94 x 3.9 x 3.7 inches	7.16 x 6.69 x 3.03 inches	7.08 x 2.99 x 6.49 inches
<b>Weight</b>	4.3 lbs	5.07 lbs	5.07 lbs
<b>Cycles</b>	5000+	2000+	2000 - 5000
<b>Price</b>	\$64.99	\$64.99	\$69.99

#### 3.2.4.1 CONCLUSION

Due to sponsor's preference, the option for the 12V 18Ah batteries will not be considered. The battery we will be using is the 2 pack of 12V 10Ah from Eco-Worthy. This battery is more expensive than the 6Ah but will provide much more power. The weights and prices between batteries with the same voltage and amp hour are very similar. The Eco-Worthy battery will be chosen due to the number of cycles, which is superior to the others.

#### 3.2.5 REGULATOR

There are a couple of components that will require power from the battery in this project. Those components are the two microcontrollers and the motor controllers. The following are the specific manufacturers and modules being used for those components: Le Potato Pi Mini, Arduino Mega 2560, (insert motor controller later), and Arducam IMX708 USB Camera Module 3. Each of these components has different power requirements that will be met using regulators. This project also

uses the Arducam IMX708 USB Camera Module 3. This component will be powered directly by the Le Potato Pi Mini, so no regulator will be needed.

To meet the requirements for senior design class, we must design the regulator on the PCB. The following components will be evaluated as a reference to our design.

### 3.2.5.1 RASPBERRY [MLB1] LIBRE COMPUTER LE POTATO PI

One of the microcontroller units that will be powered by the 24V battery is the Le Potato Pi Mini, which requires 5V DC and 2 Amps to operate. Below is a table of regulators that will be evaluated as options for this application.

TABLE

<b>Characteristics</b>	<b>LM2596S[MLB2]</b>	<b>XL6009 [MLB3]</b>	<b>Mini MP1584EN[MLB4]</b>
<b>Price</b>	\$11.99	\$11.99	\$10.99
<b>Units</b>	4	6	6
<b>Price per unit</b>	\$3.00	\$2.00	\$1.83
<b>Input Voltage</b>	4V-40V	3V-32V	4.5 V to 28 V
<b>Output Voltage</b>	1.25V - 37V	5V-35V	0.8 V to 20 V
<b>Output current</b>	Max 3A	Max 4A	Max 3A
<b>Switching Frequency</b>	150KHz	400KHz	Typically 1 MHz
<b>Conversion Efficiency</b>	Up to 92%	Up to 94%	Up to 92%
<b>Operating Temperature</b>	-45 °C to 85 °C	-40 °C to 85 °C	-45 °C to 85 °C

Of the three options mentioned above, the price is about the same, with the LMS2596S being slightly more expensive. One of the main features of the LMS2596S is the digital voltmeter display, which makes the process of installation much easier. The input voltage is not as important as the other categories since the input will always be 24V. The output voltage must include 5V, which is the final output needed. The maximum current must satisfy the minimum current which is 2.5 Amps. It is important to note that if the output voltage and current ranges also meet the requirements for the other microcontroller unit, the same type of regulator could be used for both applications. This applies for the LMS2596S and the Mini MP1584EN. Since the package contains multiple units, this could be financially beneficial to the project. The switching frequency is critical for this decision. The lowest frequency is from the LMS2596S, and the XL6009 has almost three times higher frequency. The Mini MP1584EN has a very high frequency, which makes it the best at cleaning noise. The conversion efficiencies are very similar and approximated, so they will not play a big factor in the final decision. After considering all the characteristics above, the Mini MP1584EN seems to be the best option. However, this design is very old and not recommended for design anymore.

Datasheets for each of the options above were found and analyzed. They either had a chip that is out of stock, or an old design that is not recommended to replicate anymore. Because of this, we will use the Webench tool [MLB5] to ensure that all the components are available for purchase.

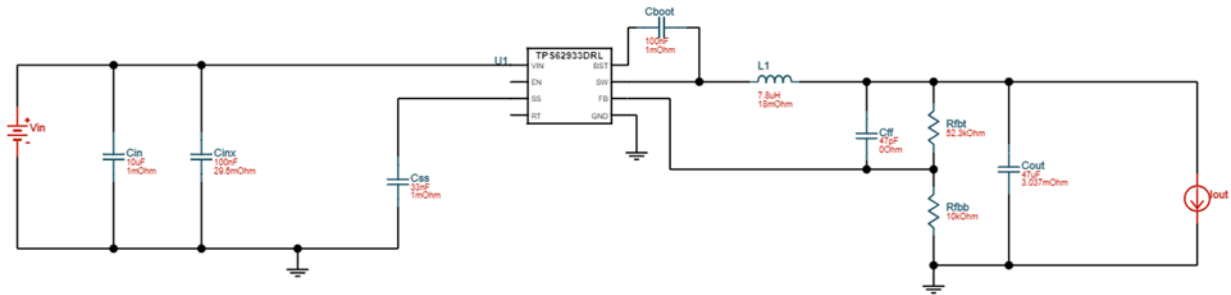


Figure 3.6 Webench Regulator Schematic for Le Potato Pi

The regulator above was designed using the TPS62933DRLR. The DC input is set to be anywhere from 8V to 26V so that the regulator works for both a 12V battery and a 24V battery, and the regulator circuit will not have to be redesigned. This circuit has 500kHz frequency, 92.9% steady state efficiency, and 43.49% duty cycle. This will be the circuit built in the PCB for this project.

### 3.2.5.2 ESP32-C6-WROOM

The ESP32-C6-WROOM operates from 3V to 3.6V at a minimum of 0.5 Amps. The table below shows some of the regulators being considered for this application.

TABLE

	LM2596 [MLB6]	DROK[MLB7]	Mini MP1584EN[MLB8]
<b>Price</b>	\$10.99	\$13.95	\$10.99
<b>Units</b>	6	1	6
<b>Price per unit</b>	\$1.83	\$13.95	\$1.83
<b>Input Voltage</b>	3.2V to 35V	8v~35v	4.5 V to 28 V
<b>Output Voltage</b>	1.25V to 30V	3~24v	0.8 V to 20 V
<b>Output current</b>	Max 3A	Max 5A	Max 3A
<b>Switching Frequency</b>	65KHz	300KHz	Typically 1 MHz
<b>Conversion Efficiency</b>	Up to 92%	Up to 95%	Up to 92%
<b>Operating Temperature</b>	-45°C to +85°C	-40~85°C	-45 °C to 85 °C

### 3.2.5.3 LM2596

The LM2596 is the regulator used for the current rover to feed the Le Potato Pi Mini. This regulator has thickened circuit boards, which means it can handle higher current levels than usual PCBs.

There is also high Q inductance, which narrows the bandwidth of the resonant circuit. Solid-state capacitors will also help with effectively filtering frequency noise.

This regulator has a potentiometer that can be used to adjust the output voltage. The converter has short circuit and over-temperature protection, both to ensure the conversion is done safely. The maximum power it can handle is 10W, so if the application required more, a heat sink would be required.

#### 3.2.5.4 DROK

This regulator has over-current protection and over-temp protection, which helps to ensure a safe conversion. The DROK regulator is also waterproof, moisture-proof, dust-proof, shock-proof. For this application, these characteristics are very important especially because of the harsh environment on the Moon. One of the great characteristics of this regulator is the anaerobic copper core wire, which will reduce resistance and increase the conductivity within the regulator. This and the synchronous rectification both help increase the efficiency.

#### 3.2.5.5 MINI MP1584EN

The output ripple of this regulator is less than 30mV, which is very low. This regulator has a potentiometer that can be used to adjust the output voltage.

#### 3.2.5.6 COMPARISON

The options above are all qualified for this application. The price of the DROK regulator is very high compared to the other options. For financial purposes, this option will not be chosen. The price per unit of the two other options is the same. Just like the previous regulator choice, the input voltage is not as relevant for the choice since they all contain 24V in the range. The voltage and current output meet the requirements for the Le Potato Pi Mini, which means the same pack of regulators could be used for both applications. The LM2596 has a much lower switching frequency, making the Mini MP1584EN much better at filtering the noise of the output. The conversion efficiencies are about the same. After all the considerations above, we will be using the Mini MP1584EN as the regulator for the ESP32.

The previous regulators will be used as reference. To meet the requirements for the PCB design, the regulators will be replicated on a personalized PCB. The schematic below was generated by Webench [MLB9] and uses the same regulator as the one from the previous section. The reason for this is to keep the design simple and reliable.

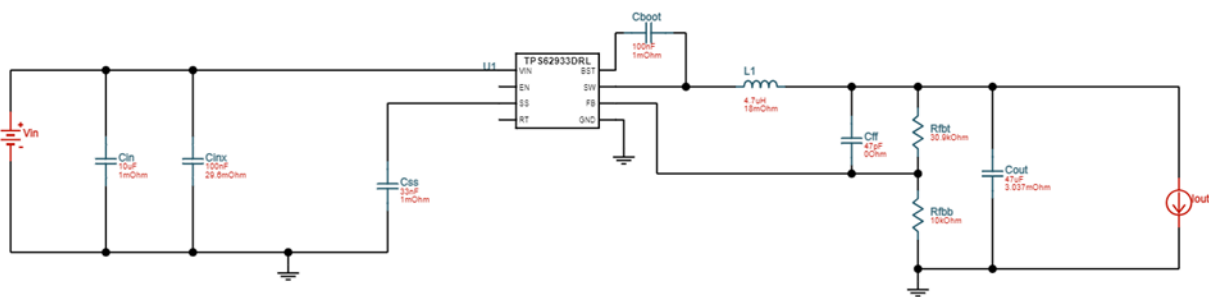


Figure 3.7 Webench Regulator Schematic Arduino Mega

This regulator was set for the same input voltage range and the circuit above has 500kHz operating frequency, 93.6% steady state efficiency, and 28.12% duty cycle.

### 3.2.5.7 RAMPS BOARD REGULATOR

The RAMPS 1.4 will be powering the motor regulators. This board has two power connectors. Both are 12V. In terms of Amps, one of them is 11A and the other is 5A. We will use the 11A connector so that the board receives more power for the motors. The voltage will be kept the same, so we will be using a regulator mostly for protection purposes.

Using the Webench tool, this is the most optimal design for a regulator that fits all of these requirements.

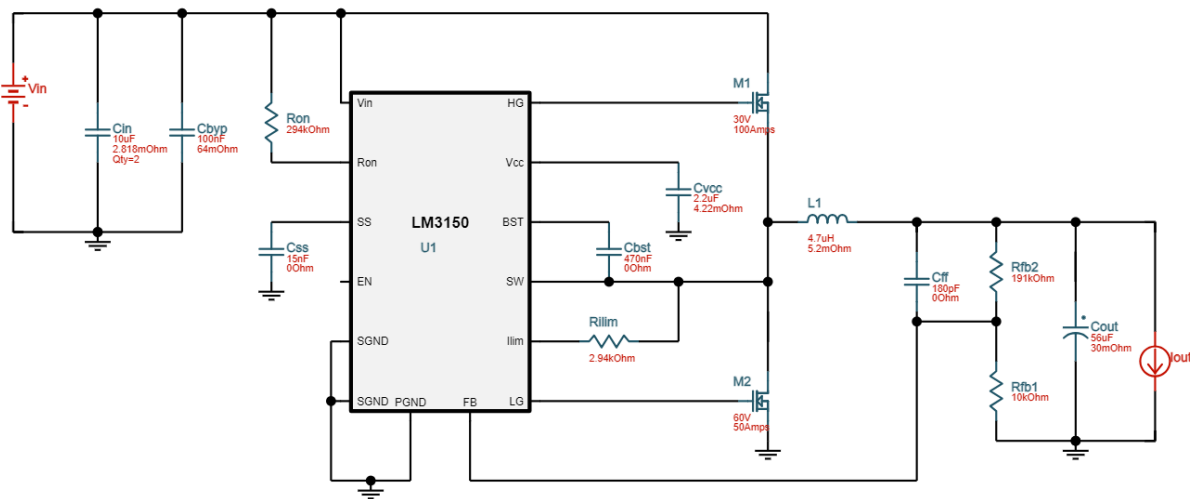


Figure 3.8 Webench Regulator Schematic for RAMPS board

This regulator has an input voltage range from 20 to 24 volts. The circuit above has 370.6kHz switching frequency, 97.1% steady state efficiency, and 50.78% duty cycle.

### 3.2.6 MOTOR

In selecting a motor, some of the most important things which need to be considered are power type, torque, and motor speed. We want to select a motor type which is able to operate on our selected power type. Additionally, with the function of the motor being to allow for movement of the rover with its wheels, as well as its bucket drums and shoulders, torque and motor speed should be considered. It would be ideal to select a motor type which will allow for us to have the most torque and speed, additionally, we do want to be able to adjust the speed externally through our motor controllers.

There are two parts of rover that will require a motor, the arm and the wheels. We are powering our system with a 24V battery, and we want to be able to control the speed of the motors to allow for us to have greater control of the rover movements, therefore the preferred general motor type is a DC motor, because this allows for us to avoid the need to utilize an inverter. As we have shoulders, bucket drums, and wheels which require motors, holding torque can be important for

all of these components, and we want to have control of the speeds. The rover will not be moving at high speeds either; therefore, we can rule out the linear motor. Stepper motors appear to be the best choice for our application because they have a simple control system and can be controlled with a microcontroller, which we already will be utilizing, and with minimal component housing, which is an important consideration because we do also have limited space in our electronic box to house all of the components we are using for the rover. Additionally, using the stepper motors over the servo motors means that we do not require a feedback device, again helping us reduce components needed as well as allowing for less complexity in our system design.

Due to the existing structure of the rover and the sponsor desire to maintain the current motors, the stepper motors selected are the NEMA 17 for the wheels and the bucket drums and the NEMA 23 for the shoulders. These have specific motor sizes which the rover is already designed to fit. The NEMA 23 has more torque in comparison to the NEMA 17, which makes it more suitable for the shoulder. Since increased torque is less critical for the wheels, it is suitable to use the NEMA 17 for the sake of having a small diameter. The NEMA 17 and NEMA 23 single stack stepper motors are rated for 2 amps and 2.2 amps respectively.

### 3.2.7 MOTOR CONTROLLERS

Motor drivers are required in order to interface the microcontroller unit and allow for control and operation of the stepper motors, they ensure that the necessary current and voltage levels are applied to control movement and positioning. They generate the pulses needed to allow for movement and determine the direction by with their pulse sequence and polarity. They also ensure that the heat generation is minimized and can micro step to allow for smooth motion. Important things to consider for selecting a motor driver is the stepper motor's current rating, for the NEMA 17 this is 1.5A and for the NEMA 23 this can be 2.4A, 3.0A, or 6.0A.

Currently, our rover employs the A4988 driver for its wheels and the DRV8825 for its arm. The A4988 complete microstepping driver has a built-in translator and offers five selectable stepping modes, enabling flexibility in our control system. Rated for a supply voltage of up to 35V and an output current of 2A, this driver is suitable to our existing voltage supply of 12V, with the added advantage of being compatible with an upgraded voltage supply of 24V, which we are considering to be a goal for our project.

The current motor driver shield, RAMPS 1.4, utilized in our rover is rated at 12V, but it possesses the potential for modification to operate on a 24V supply. This adaptability ensures that we can seamlessly transition to the higher voltage supply without the need for a complete overhaul, additionally with plans to design a customized motor driver shield, we should be able to house additional motor drivers and we can adjust the needed components of the RAMPS 1.4 to be suitable for our current motor drivers or different options of motor drivers.

While these drivers serve our current needs, it's essential to explore other options that might offer performance benefits that may make changes to the existing system worthwhile.

The DRV8825 driver operates as a dual H-bridge driver with a microstepping indexer, with its intended use being to drive bipolar stepper motors. With proper heat sinking, it is able to drive up to 2.5 A of current, and 1.5A of current without any heat sinks. This is also a commonly used



replacement for the A4988 because it is able to be connected to the RAMPS without any modifications required.

The DRV8835 driver operates as a dual H-bridge motor driver suitable for driving small DC motors or bipolar stepper motors. However, it's worth noting that its limited current capacity may render it less ideal for high-performance stepper motor tasks.

For more modern options, we have the TMC2209, a stepper motor driver that has silent operation, efficient current control, and extensive configurability. This driver excels in microstepping and is well-equipped to handle high-performance applications but it is limited to only the UART communication protocol.

Lastly, the ULN2003, while capable of driving inductive loads like stepper motors, falls into the category of basic motor control. Its lack of microstepping capabilities limits its suitability for intricate tasks, but we do not necessarily need microstepping for the wheels.

In conclusion, our choice of a motor driver hinges on the specific motor type, whether it be a stepper motor or brushless DC motor. While our current drivers, the A4988 and DRV8825, serve our rover's needs, exploring modern alternatives like the TMC2209 could potentially allow for new levels of performance and functionality.

*Table 3.18 Candidate Motor Controller Comparison*

<b>Criteria/ Drivers</b>	<b>A4988</b>	<b>DRV8825</b>	<b>DRV8835</b>	<b>TMC2209</b>	<b>ULN2003</b>	<b>TB67S249FTG</b>
<b>Stepping Modes</b>	1, 1/2, 1/4, 1/8, 1/16	1, 1/2, 1/4, 1/8, 1/16, 1/32	n/a	1/8, 1/16, 1/32, 1/64, 1/256	1	1, 1/2, 1/4, 1/8, 1/16, 1/32
<b>Supply Voltage</b>	8V to 35V	8.2V to 45V	2V to 11V	4.75V to 29V	5V to 30V	10V to 47V
<b>Supply Peak Current</b>	2A	2.5A	0A to 1.5A	2.8	500 mA	4.5A
<b>Overheat Protection</b>	No	Yes	Yes	Yes	No	Yes
<b>Price (\$)</b>	2.04	2.58	4.95	5.75	2.4	14.95

When selecting the motor controller, price serves as a major factor in the decision. As the current rover is equipped with A4988, which is a very inexpensive and readily available option. There must be strong enough justification to substitute a driver which costs more. Of the options investigated, the only ones that appear to be close in cost to the A4988 are the DRV8825 and the ULN2003. However, the ULN2003 can instantly be ruled out due to the 500 mA peak current supplied because even if we do not run the motors at their max current, we want to have the ability to do so available to us. The DRV 8825 has the added benefit of being able to drive a reduced current without a heatsink. Since the intended purpose of upgrading the voltage supply to 24V is to reduce current, we should be able to operate these drivers without a need for a heat sink and have them perform equivalently to the A4988, additionally, by using the DRV8825, there is less complication in changes to the RAMPS board as this drivers are a common replacement therefore there is good compatibility for the board and also the size of the motor driver carrier fits the board without need for any adjustments.

### 3.2.8 MOTOR SHIELD

The motor shield that we are taking inspiration from is the RAMPS 1.4 board. This board is commonly used in computer number control machining, such as with 3D printers. It has a large amount of practicality because it is designed to be placed on top of an Arduino Mega 2560 and have the motor drivers and motors connected to it. The entire board is powered and through this it is able to power the motors and the Arduino rather than needing separate power sources for each item. In addition to the connections for power, the motors/motor drivers, and Arduino, there are some additional major connections available for the 3D printing application, including running a fan, heating the bed of the printer, and additional auxiliary connections for additional peripherals such as an LCD display, or an SD card reader. There are additional pins available in addition to the ones listed here.

The existing design of the rover utilizes this board by using the 5A power supply connection, and three of the motor driver and motor connections, therefore the remaining available connections on this board go unused. The goal for our project is to take this existing motor shield and redesign it to serve the specific purpose of application in this rover, which 10 motor driver connections available to use instead of 5, allowing for each wheel, along with bucket drums on all four sides, and a front and rear shoulder to be controlled with its own motor driver.

### 3.2.9 ANTENNA

*Table 3.19 Candidate Antenna Comparison*

	<b>PC140</b>	<b>WPC.25A</b>	<b>FXP74</b>	<b>PC17</b>	<b>FXP70</b>
<b>Average Gain (dB)</b>	-1.92	-1.14	-2	-3.6	-2
<b>Peak Gain (dBi)</b>	1.67	5.15	4	.9	1.1
<b>Efficiency (%)</b>	64	76.9	50	44	63.7
<b>VSWR</b>	<2	<2	<2	<1.5	<1.5
<b>Polarization</b>	RHCP	Linear	Linear	Linear	Linear

<b>Cost (\$)</b>	20.96				
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### 3.2.9.1 PC140

The PC140 is an embedded, low-profile, circularly polarized (RHCP) antenna that operates in the 2.4GHz band. It is suitable for applications like the rover in this project, where orientation to a stationary tower may constantly change. With dimensions of 57\*57\*0.97mm and a weight of 5.7 grams, the antenna is constructed from FR4 and includes a 100mm coaxial cable and IPEX connector. Its compact size is a desirable feature as the components within the rover need to maintain a small form factor. A double-sided 3M adhesive also ensures easy mounting on the rover's non-metal surfaces.

In the 2.4GHz band, the antenna showcases an axial ratio between 3.2 and 3.75, demonstrating its strengthened circular polarization. It offers a peak gain of 2dBi and a typical efficiency of over 60% across Wi-Fi bands, making it suitable for direct mounting on plastic or glass covers on the rover. Performance-wise, the antenna provides an average gain ranging from -1.92 to -1.83 dB and an efficiency between 64% and 65%, with peak gains between 1.67 and 1.54 dBi. These characteristics are optimal for the omnidirectional communication required by the rover to maintain a stable link with the stationary tower.

Further supporting its use in this application, the PC140's Voltage Standing Wave Ratio (VSWR) is less than 2, and the return loss is less than -10 dB, with an impedance of 50 Ohms.

Environmentally, the antenna is designed to function within a temperature range of -40°C to +85°C, aligning well with the expected conditions the rover may encounter.

### 3.2.9.2 WPC.25.A.07.0150C

The WPC.25.A.07.0150C Ceramic Patch Antenna with cable is designed to operate at 2.4GHz. It consists of an embedded patch antenna, mini-coax cable, and connector. The antenna has its own ground PCB carrier, making it ground-independent.

Moving on to the specifications, the electrical characteristics of the antenna include a frequency band of 2400-2500MHz, an efficiency of 76.9%, an average gain of -1.14dB, a peak gain of 5.15dBi, an impedance of 50Ω, and an omnidirectional radiation pattern. The maximum input power supported by the antenna is 2W. It is important to note that this antenna is linearly polarized, which is not optimal for this application. Nevertheless, it is essential to include an antenna with the above specifications if the chosen specifications are unsatisfactory.

Regarding mechanical details, the antenna has 25 x 25 x 5.5mm dimensions. It is connected using a 1.37 mini coaxial cable with a length of 150mm and an IPEX MHF1 connector.

The antenna is designed to withstand environmental conditions, with a temperature range of -40°C to 85°C and non-condensing humidity up to 95% RH at 65°C.

Overall, the WPC.25A 2.4GHz Ceramic Patch Antenna with cable offers reliable performance in various wireless communication applications within the 2.4GHz band.

### 3.2.9.3 FXP74.07.0100A

The FXP74 Black Diamond antenna is a small, ultra-low-profile antenna designed for the 2.4GHz band, including Bluetooth, Zigbee, and Wi-Fi applications. The antenna is made from a flexible polymer with a compact form factor, with double-sided 3M tape for easy and secure mounting.

Regarding specifications, the FXP74 antenna supports communication systems, including Bluetooth, Wi-Fi, Zigbee, and the 2.4GHz ISM band. It has an efficiency of 50%, a gain of 4dBi, a return loss of less than -10dB, an impedance of 50 Ohms, and a VSWR of  $\leq 2:1$ . The antenna has a linear polarization and can handle up to 5W of power.

It has dimensions of 14mm\*7.0mm\*0.1mm, weighs 1.2g, and uses an MHFI (U.FL compatible) connector. The antenna is connected using a standard mini-coax 1.13mm cable with a length of 100mm. It is designed to operate within a temperature range of -40 °C to +85 °C and can withstand various environmental conditions.

### 3.2.9.4 PC17.07.0070A

The PC.17 is an ultra-miniature PCB antenna designed for 2.4GHz band applications, including Wi-Fi, Bluetooth, and ISM. It features a robust antenna and mini coaxial cable, with compact dimensions of 24mm x 11mm x 0.8mm, allowing it to fit into small spaces while maintaining optimum performance.

It has an efficiency of 44%, a peak gain of 0.9dBi, and an average gain of -3.6dBi. The antenna has a return loss of -12dB, an impedance of 50 Ohms, and a VSWR of  $\leq 1.5:1$ . It features linear polarization and can handle a power of 2W.

Mechanically, the PC.17 antenna has 10.75mm x 24mm x 0.8mm dimensions. It utilizes an MHFI (U.FL compatible) connector and a standard Mini-Coax 1.13mm cable. The antenna operates within a temperature range of -40°C to +85°C for operation and storage. It is also RoHS compliant.

Overall, the PC.17 antenna provides a compact and efficient solution for wireless communication in the 2.4GHz band, offering customization options and meeting environmental standards.

### 3.2.9.5 FXP70.07.0053A

The FXP70 Freedom 2.4GHz Antenna is a versatile antenna that operates on Wi-Fi, ZigBee, Bluetooth, and ISM bands at 2.4GHz. The antenna is precisely engineered to work with different plastic materials, with the testing done using a 2mm thick ABS plastic as a baseline.

Regarding specifications, the antenna exhibits an efficiency of 63.7% on a 2mm ABS material and 30.5% in free space. The average gain is -2dB on 2mm ABS and -5.2dB in free space, while the peak gain is 1.1dBi on 2mm ABS and -1.9dBi in free space. It has an impedance of 50  $\Omega$ , linear polarization, an omnidirectional radiation pattern, and a VSWR of  $\leq 1.5:1$ . The antenna can handle a maximum input power of 5W.

Mechanically, the FXP70 antenna has 27 x 25 x 0.08 mm dimensions and weighs 1.2g. It utilizes an MHFI (U.FL compatible) connector and a 53mm Mini-Coax 1.13mm cable. The antenna is affixed using 3M 467 adhesive.

The FXP70 antenna is designed to operate within a temperature range of  $-40^{\circ}\text{C}$  to  $85^{\circ}\text{C}$ , ensuring durability in various environmental conditions. It can withstand non-condensing humidity levels of up to 95% RH at  $65^{\circ}\text{C}$ .

#### 3.2.9.6 ANTENNA CHOICE

The PC140 is the superior choice among the available antennas, primarily because of its circular polarization. This feature is indispensable for communication between objects with changing displacements. While some other antennas may boast greater efficiency or directivity, none of them offer circular polarization. Therefore, in the context of specific requirements, better efficiency becomes secondary. The unique capability of the PC140 to provide circular polarization makes it the best option for the task at hand.

### 4 RELATED STANDARDS AND REAL-WORLD DESIGN CONSTRAINTS

#### 4.1 RELATED STANDARDS

The standards that are relevant to the project are listed below. Although most of these standards are easily implemented with tools that are readily available, some of these standards require facilities and tools that are complex and expensive, making them impossible to access for the purposes of this project. Also, it is important to note that this project is just a proof of concept; the project is only an example to show that certain technologies can be implemented on a rover.

One of the most important battery standards is the IEC 60086[MLB1] -1. This standard regulates many different categories within batteries such as access to children, electrochemical system requirements, performance characteristics, packaging, disposal, and many others.

Another important standard for batteries is the IEC 60086-2. This [MLB2] mostly regulates the physical dimensions of batteries, discharge test conditions and discharge performance requirements.

Zigbee is a low-power, wireless networking standard suitable for low cost, low throughput, and reliable communication between devices. The reduction in bandwidth trades off with an increase in battery life. It is based on the IEEE 802.15.4 standard and operates in the 2.4 GHz, 868 MHz, and 915 MHz bands. The standard is maintained by the IEEE 802.15 working group.

Wi-Fi or IEEE 802.11 is a set of standards for wireless local area networking. IEEE 802.11 uses various frequencies such as 2.4 GHz and 5GHz. The biggest application for the standard is internet protocol traffic. The standard is maintained by the IEEE Standards Committee, IEEE 802.

#### 4.2 ECONOMIC CONSTRAINTS

Some important economic constraints to consider is that we do have a limited budget of \$650 to work with for this project.

Our battery selection, for instance, stands as a significant cost factor. While the market offers batteries with varying price points, our preference leans toward the lower end of the price range. This decision not only allows us to stay within our budgetary constraints but also frees up financial resources for other needed components.

Furthermore, in the realm of robotics and engineering, cost-efficiency extends beyond the initial purchase price. It encompasses the entire lifecycle of our project, from assembly to maintenance

and, if necessary, replacement. To this end, we need to consider cheaper and readily available items. By doing so, we not only reduce upfront costs but also allow for more affordable and accessible part replacements, should the need arise.

#### 4.3 TIME CONSTRAINTS

The most significant limiting factor of finishing a project is time. Even if one has unlimited funds and resources, a deadline will still come. In the case of this project, multiple failure points are a direct result of time, such as too many goals to achieve, inability to get the required components in time, and even needing to be able to finish the required paper or meet milestones.

The project sponsor requires specific requirements, such as a certain amount of motor controllers. These requirements are fundamental to the project but are different from the limit of the specifications that the project can achieve. By increasing capabilities, the project can move beyond a primary rover to a more complex system. These capabilities require time to fully realize, trading off with time that can be spent on ensuring that the basic requirements are completely troubleshooted. Sometimes, these capabilities are relatively easy to realize, such as ensuring the rover can host even more motor controllers by building its foundation, like supplying more power. This is an example of a regular goal for the project. Another capability is the ability to wirelessly charge the rover wirelessly, increasing its autonomy. This is an example of a stretch goal. There are multiple reasons: the complexity this goal would require would be too great for such a short amount of time; the fact that it is not fundamental to the operation of the rover and, therefore, outside the scope of the project. A helpful thing about stretch goals is that if they are not achieved, there is no harm to the final product except if time is invested. Besides stretch goals, regular goals must be achieved, especially the ones fundamental to the rover's operation, which require loads of time to complete.

An advantage of researching components is that one might come up with multiple ready for the task. This advantage is because the most optimal component might be out of stock. In this case, one would pick the next best component, order it, and integrate it into the project. However, in the case that only one component can fulfill the needs of the project, the time waiting for it can cause a severe delay in meeting project deadlines. Even though other tasks could be completed while waiting for the part, it still needs to be received with enough time to properly integrate it into the project and troubleshoot it thoroughly to prevent embarrassment and failure. An example specific to this project could be a Le Potato Pi module that uses Zigbee but can also host an external antenna. Only some modules can do this. If the one module that can do both tasks is out of stock, the project could be out of luck.

Finishing the paper or the project milestones could benefit passing the class. For example, if the 60-page milestone is not met, the result could be failing the class, which could put one's whole career in jeopardy. The time constraint is inherent to life. The only way to mitigate its impacts is to develop time management skills. The biggest among them is decreasing procrastination. By finishing the paper or meeting project milestones early, one can allocate more time to integrating the parts and testing, resulting in a fantastic project. This avenue leaves more time to focus on other courses and not sacrifice a grade point average for Senior Design One and Two. Time management is critical to the eradication of procrastination. As an expert consultant essential to both University of Central Florida and the project once said, "If you do not like a certain food, why would you want to chew it longer?" Under the tutelage of Dr. Chan, both his wisdom and threat of disappointment, the rover group pushes this project past procrastination to success.

#### 4.4 SAFETY CONSTRAINTS

Although safety is not a paramount concern while operating on the moon, when testing and operating the rover on Earth, there are many factors that must be accounted for.

A clear and present safety concern is exposure to Radio Frequency energy and its biological effects. The most obvious and verified effect is the heating of the tissue by the non-ionized RF radiation. High exposure amounts can result in heating of tissue and an increase in body temperature. The consequences could be as severe as tissue damage because of the human body's inability to dissipate the heat, especially within the eyes and testes. Any radiation level lower than thermal heating requires has not been verified to cause any effects such as cancer.

Another safety concern is the limit on transmit power. The Federal Communication Commission and industry norms limit modem transmit power to two Watts. This is extremely important as if one were to transmit more than two watts, the resulting leakage into other bands would have a higher power level as well which can cause possible interference of frequencies exclusively used by police or the military. Therefore, it is important that the transmitted is not able to transmit higher the two watts and it is also important to test adjacent channel leakage regardless of transmit power in an effort to prevent interference into other bands.

In terms of practical safety concerns in our own design and testing. Tools being used, such as a solder iron provide additional safety risk due to working at high temperatures while coming in contact with highly conductive materials. Improper use of the iron or carelessness around it can result in severe burns and prolonged exposure to solder fumes can also be toxic. Additionally, when working with our electrical components, electrical overstress can cause a release of smoke which could potentially be toxic or result in a fire. These risks can be reduced by taking extra precautions when working with these tools and our components and ensuring all guidelines are followed for devices used.

#### 4.5 ENVIRONMENTAL, SUSTAINABILITY, AND SOCIOPOLITICAL CONSTRAINTS

This project involves the concept of lunar exploration. Along with that topic, there are many constraints. In terms of the environment, there are two main concerns. One of them is the harm that lunar exploration can cause to the environment on the Moon. Things such as the use of technology and its impact on the magnetic field and landscape. Another concern is the use of batteries on the moon since an explosion could be extremely harmful to the environment. There are also socio political constraints that come with lunar exploration. With the great political involvement in investments and regulations, lunar exploration becomes heavily reliant on socio political decisions.

##### 4.5.1 ENVIRONMENTAL AND SUSTAINABILITY CONSTRAINTS OF LUNAR EXPLORATION

There are many constraints related to Moon exploration. One of them is about environmental and sustainability concerns. In this application, our environment is the Moon, which is a sensitive and polemic environment. Engineers are doing what is possible to minimize the interference of technology and human impact on the Moon. One example is the use of magnetometers on spacecraft. This component must be extended on a boom so that it decreases the impact of the aircraft on the magnetic field [10[MLB1] ]. In this project, we must consider things like the effect of bringing a lithium-ion battery to space and what impact it can have on the environment.

Environmentalists argue that there should not be any human alterations to the Moon such as formation of new craters or any landscape alteration. But there are scientific groups interested in analyzing the environment and collecting data. There must be a balance between the environmentalist groups and scientific groups. Debates between the two are common and require factual evidence to reach proper conclusions. This is not possible since there has not been a lot of research done on the Moon. Once scientists have conducted enough research, the debates will likely result in more concrete conclusions.

#### 4.5.2 ENVIRONMENTAL IMPACT OF BATTERIES

Batteries come with serious environmental concerns. Electronic waste, also known as e-waste, is one of the most pressing issues for the environment and even humans. If not properly disposed of, electronic waste can be very harmful to the environment. This has been a rising issue on Earth, and we certainly don't want to bring it to the Moon. Batteries contain toxic chemicals such as lead, mercury, and arsenic [[MLB2] ]. This is tied to the sociopolitical matter of lunar exploration. Damaged or unstable batteries can cause the component to overheat and explode, which can be extremely dangerous and harmful for both humans and the environment. The explosion caused by the battery is not easy to extinguish. Fire extinguishers do not work on lithium-ion batteries. The fire is easily spread and is very dangerous. One of the concerns with batteries is that overheating can go unnoticed until it is too late to prevent fire. The explosion can also pass to other components and cause a lot of damage to other parts[MLB3] .

#### 4.5.3 SOCIO-POLITICAL CONSTRAINTS OF LUNAR EXPLORATION

Space exploration started with politics. It began as a space run between the United States and the Soviet Union. That was the main incentive to lunar exploration and can still be considered one of the main incentives today. The current socio-political situation mostly revolves around the Artemis program. NASA plans on bringing humans back to the Moon after more than 50 years [MLB4] [] The first landing is expected to be in 2025, which is very close. There are many challenges that come with sending humans to the Moon, and a lot of them are sociopolitical.

### 5 CHATGPT

#### 5.1 CASE STUDY #1 (MARIA BONINA ZIMATH)

##### 5.1.1 BENEFITS


One of the greatest benefits of using ChatGPT is how quickly data can be retrieved. With a small paragraph input, the program can do hours' worth of research in a few seconds. This can be very helpful in the beginning of the research process, when deciding relevant topics to be discussed. There is such a wide range of technologies to be studied that it can take a long amount of time to decide which ones to consider for research. Reading about the technologies and understanding the relevant parameters is the most time-consuming part of the project. After defining which topics to cover, it becomes much easier to find the most useful resources and writing.


The key is to give as much information as possible, so that the AI is able to understand the question. Another possibility is telling ChatGPT to ask back any questions that may help it make a better answer. When researching batteries, for example, one of the useful first steps was to ask ChatGPT which battery chemistries are relevant based on given application parameters. By starting from the




suggested chemistries, it became much easier to define the most relevant technologies to be studied.

Another way to use ChatGPT was to ask for relevant characteristics to be considered for each battery chemistry. This was helpful when identifying the most important variables to study and include in the comparison table. Below is an example of how ChatGPT was used to come up with important characteristics to compare between different battery chemistries. Note that all the information received from ChatGPT was fact checked in research articles.

 make a chart comparing important characteristics for battery chemistries. Use lithium ion, lithium polymer, and lead aci

 Sure! Here's a comparison chart of important characteristics for lithium-ion, lithium polymer, and lead-acid battery chemistries:

Characteristic	Lithium-Ion	Lithium Polymer	Lead-Acid
Energy Density	High	High	Low to Moderate
Power Density	High	High	Low to Moderate
Cycle Life	Moderate to High	Moderate to High	Moderate
Self-Discharge Rate	Low	Low	High
Memory Effect	None	None	None
Charging Time	Moderate to Fast	Moderate to Fast	Slow
Cost	Moderate to High	Moderate to High	Low to Moderate
Maintenance	Maintenance-Free	Maintenance-Free	Requires Maintenance
Environmental Impact	Low	Low	High
Voltage per Cell	3.6 - 3.7 Volts	3.6 - 3.7 Volts	2 Volts

 Regenerate

A great feature is the user-feedback. The student can respond to each answer generated by the AI with a correction or even request to elaborate on any previous answers. This allows the student to receive quick information on very specific topics as well as learning assistance. This was another helpful feature when online resources didn't quite elaborate on a specific part of the topic. If something is not clear, ChatGPT can provide a more elaborate answer with different explanations until the student can understand the topic. When using the internet and reading articles, students are unable to ask questions, making the learning process much harder and time consuming.

### 5.1.2 DRAWBACKS

There are many drawbacks to using this platform, especially for technical information. ChatGPT is an ungrounded Artificial Intelligence model. This means that the platform does not have real-world connection or experience related to the information it gives. ChatGPT is unable to comprehend its training data on a deep level and may make incorrect assumptions. The model does not have human level reasoning besides the repetition of patterns.

For this application, the most concerning drawback is the inaccuracy. ChatGPT is unable to verify accuracy of data like humans do, since the responses are solely based on patterns from old data. This could lead to incorrect data that is given by ChatGPT. This means that any fact given by the

platform must be researched and confirmed by trusted sources. It can take more time to individually check every one of the facts given by ChatGPT than doing research without the AI platform. Even if the student is aware that the data may not be correct, it can mislead the user to biased research. For example, if ChatGPT suggests a topic that it believes to be important to investigate for the research section, that may not be the most recent technology.

Using ChatGPT means that facts can be outdated. The database used to train the AI is never going to be the most recent. Especially considering the quick growth in technology, using ChatGPT for technical research may bring statements that are true but not at that point in time. It may have been correct and even the most efficient at the time the AI was trained, but not when the question was asked on ChatGPT. Since the information is not updated in real time, the technology may have changed and therefore not be the best solution anymore. The technology may also have been banned, or a new regulation could pass that changes the feasibility of the solution. There are many causes that could lead to a different ChatGPT response if it was updated in real time.

There is a bias that comes with the limited amount of data resources used to train the model. ChatGPT is unable to look for data outside of its training data, meaning it will not actually do research for a student. Coming up with a conclusion based on facts requires a certain level of understanding. Since the platform does not have the same level of understanding as a human, AI may lead to ambiguous answers. For example, the model may not have access to certain regulations that may make a certain technology unfeasible to the project. The user would not be aware of this when using ChatGPT. Even if the model was updated, the platform is unable to cite sources, and therefore it would still not be fully reliable.

Another problem that may arise with the use of ChatGPT is not giving it enough information to answer the question. A person with technical experience would know what information is needed to make the correct assumptions and give a logical answer. ChatGPT is unable to recognize missing information about a project. This means that depending on which parts of the project are explained to the AI, there will be a different answer. A very small part of the project that may seem obvious to explain to a human may drastically change the answer given by the AI model.

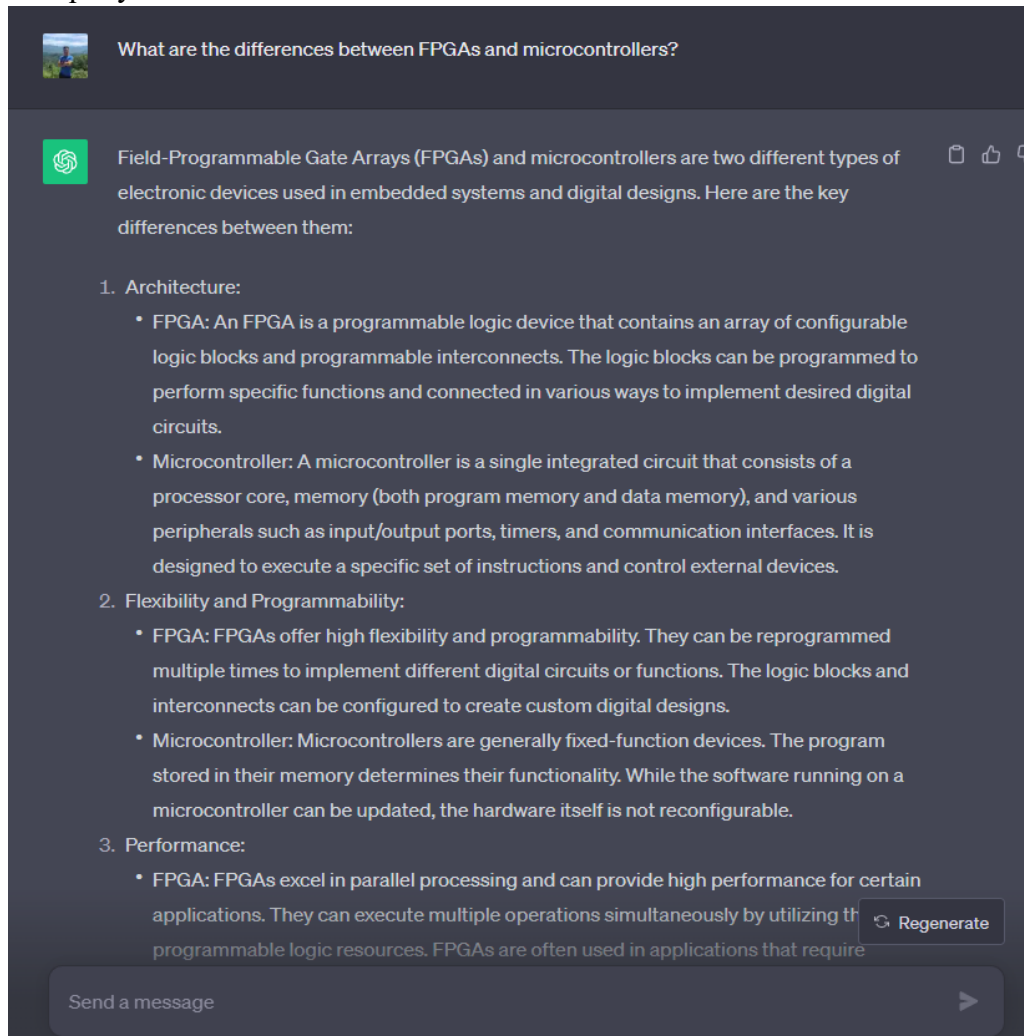
A user can ask ChatGPT to explain its answers. The platform will provide an answer to its best ability. However, the AI model is not meant for that. It is not made to provide proper logical reasoning that justifies the answer and explains the decision-making process. As much as it can create an answer that makes it seem like it does, that is not the main purpose of the platform, and it is not a reliable justification. That answer is solely based on patterns observed during training and not logical reasoning. For this reason, ChatGPT should not technically be used to explain decision making or any sort of explanations.

## 5.2 CASE STUDY #2 (BRANDON NGUYEN)

ChatGPT is an excellent tool for learning new concepts and obtaining summarizations of concepts and comparisons of different platforms of technology.

When beginning research on microcontrollers, it was necessary to consider both FPGAs and microcontrollers as a solution to the project's electronic computing needs. ChatGPT was used in beginning the initial assessment on whether FPGAs or microcontrollers were best suited for this rover project. The following phrase was queried into the ChatGPT text chat: "What are the

differences between FPGAs and microcontrollers?” The following image displays the output given the previous query:



*Figure 5.1 ChatGPT output in response to “What are the differences between FPGAs and microcontrollers?”*

In response to the query, ChatGPT presents five points of comparison (only three pictured in the figure) between microcontrollers and FPGAs and summarizes the overall comparison of the two technologies. Those five points were related to architecture, flexibility and programmability, performance, development and prototyping, and cost and complexity. This high-level general comparison of FPGAs and microcontrollers provided a clear pathway towards the decision to be made between FPGAs and microcontrollers and what other information needed to be gathered in making that decision.

ChatGPT was also useful in listing out the various existing camera interface technologies. As this area of technology was relatively unfamiliar to me, having ChatGPT find the various camera interface technologies within the micro-computing context was incredibly useful and saved a considerable amount of time. The phrase, “What are different technologies used to interface cameras used for microcontrollers” was used to query ChatGPT and the language model gave an output explaining the five commonly used interfaces; those being SPI, I2C, Parallel Interface, USB, and

MIPI CSI-2. From ChatGPT's explanation of each interface, it was easy to rule out which interfaces would be suitable for our project given that the goal is to stream high framerate and high-resolution video.

In the process of developing the process for video transmission, ChatGPT proved to be useful in learning the high-level general processes in an application that streams video wirelessly. The information obtained from ChatGPT allowed me to determine that the selected microcontroller needs to be powerful enough to capture, compress, and packetize video data in a timely manner to allow for low-latency and high-frame rate video streaming. In addition, the presentation of compression as a factor in video transmission brought to attention that there are standards of compression that the selected microcontroller should be able to support. Finally, the network infrastructure needs to have enough bandwidth to support the amount of data that would be transmitted through streaming video, which brings into question which wireless standards to deploy that would adequately meet the needs of the project.

Finally, ChatGPT served as a great summarization tool of massive open-source libraries to aid in deciding which application programming interfaces would be most suitable to the project's needs and constraints as well as judging general ease of use in development. In this matter, ChatGPT saves a lot of time by eliminating the need to read through endless amounts of documentation on the various APIs for camera programming. However, it does not eliminate the need to do more in-depth reading and research on the selected APIs for development once it has been determined that those are the best for the project's needs.

The downside to using ChatGPT is that information can sometimes be inaccurate perhaps due to outdated information, or even through inadvertently sourcing false information. During my use for Senior Design, I found that ChatGPT had just one instance where information was inconsistent with findings from other sources on the internet. ChatGPT is also limited in the aspect that it cannot effectively design any complex systems. It is merely a culmination of a mass amount of information and cannot replicate human intellect in the aspect of "design".

### 5.3 CASE STUDY #3 (ELI COUTURE)

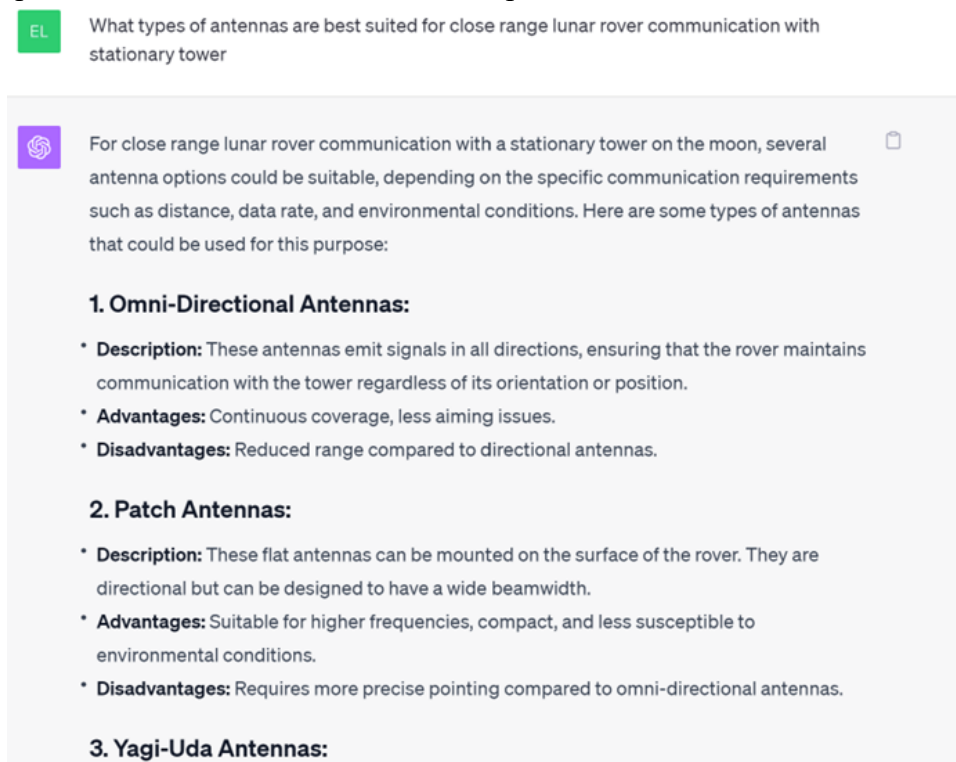
ChatGPT can be a valuable tool for technical writing and component selection in various projects. Specifically, in this example, it can be helpful for antenna selection by generating informative content and providing technical specifications. For technical writing, ChatGPT can assist in creating technically correct content. It can generate text with similar wording or vocabulary to other technical papers on related subjects. Considering its vast amount of data, it can provide explanations, guidelines, and detailed information on many technical topics. This can be especially useful for writers needing assistance understanding complex technical concepts.

Regarding part selection, specifically antennas, ChatGPT provides information about different antennas, their characteristics, and applications. By offering insights into various factors for antenna selection, such as frequency range, gain, impedance, polarization, radiation pattern, and physical dimensions, it can help narrow down the many options. Also, it can assist in explaining technical specifications and suggest how different antennas might be suitable for applications.

While using ChatGPT showcases advantages, it is pivotal to acknowledge some limitations, especially in technical contexts like writing and antenna selection. Firstly, it is based on data from when it was last trained and, therefore, does not have access to real-time information or recent technological developments. This can be particularly detrimental in technical writing and part

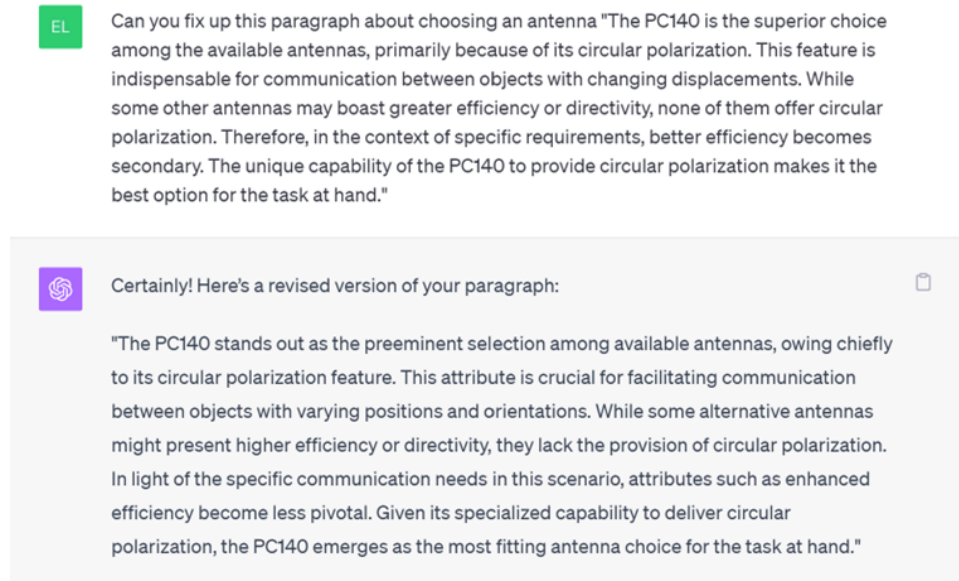
selection, where the most current and accurate data is paramount to producing reliable content and making informed decisions. Moreover, ChatGPT, most of the time, needs help understanding highly technical lines of questioning, which can result in generating answers that are too general for technical writing.

Another shortcoming is understanding context and the inability to provide user-specific recommendations. While it can generate responses based on information in its training data, it needs to possess the capability to comprehend the nuanced needs and constraints that might be present in specific technical documents. For instance, when selecting an antenna, an engineer might need to consider variables like budget, spatial constraints, and integration with other systems, which ChatGPT cannot evaluate. Therefore, while it can serve as a helpful starting point or a supplementary tool, relying solely on ChatGPT for technical writing or part selection could lead to suboptimal outcomes. Here are some examples below.



*Figure 5.2 ChatGPT query for summarized information*

This example demonstrates ChatGPT's ability to point one in the right direction when starting out a project. Although it cannot evaluate all the restrictions imposed by the project, it provides an initial point where one can start to research and learn more about a given subject.



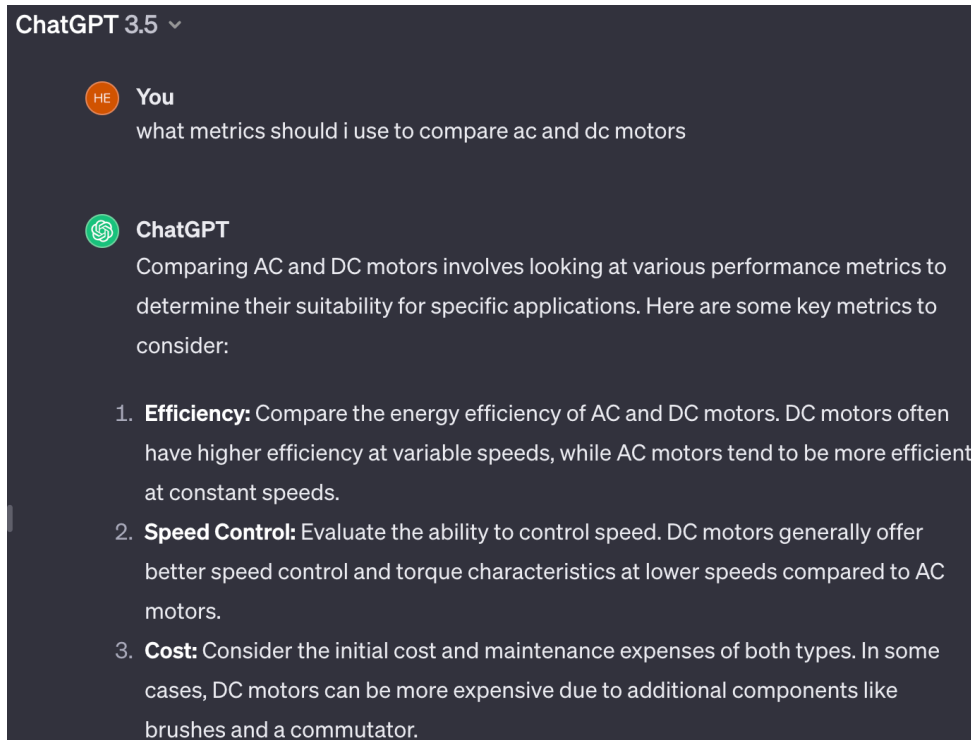
*Figure 5.3 ChatGPT Grammatical Correction Functionality*

This example demonstrates ChatGPT's ability to spruce up writing that may be riddled with errors or lacking in the correct vocabulary. However, ChatGPT tends to go overboard with the language it uses often writing in passive voice or artificially extending sentences. Therefore, I have found it best to use Grammarly for most of the editing as it still enables me to write in my voice while maintaining correct grammar for a technical paper.

#### 5.4 CASE STUDY #4 (NINA TRAN)

As we continue to grow as a more technologically advanced world, tools like ChatGPT are becoming increasingly more prevalent in our daily lives. There are many uses for ChatGPT both which can be beneficial to us and harmful to us.

In writing this paper, ChatGPT can be very useful to use when trying to come up with criteria for comparisons. By using ChatGPT properly, it can be used to help come up with a starting point which writing research for part or technology comparisons. The screenshot below provides an example of me asking ChatGPT what metrics I should use to compare AC and DC motors.



Needs caption

From this question, I get various suggestions from ChatGPT on what I should consider comparing for looking at AC motors compared to DC motors. I can take these suggestions, deciding which ones I think are valuable to evaluate and disregarding ones that I do not think are necessary and do more research on each of them to facilitate my writing and help me generate a table for comparison. ChatGPT is also able to come up with these at a much faster speed than I would be able to generate them myself, allowing for my work rate to be greatly sped up and the quality of work to be improved as I can now dedicate more of my time and effort towards developing the writing and more valuable research.

Additional valid and beneficial uses of ChatGPT are for checking grammar or improving writing. I could provide ChatGPT a paragraph and ask it to check and correct my grammar. This can be done quickly and efficiently through ChatGPT, again saving lots of time when it comes to writing a paper. If I noticed that I was using a word excessively, I could also use ChatGPT as a quick thesaurus search to help improve my word choice. Thus, assisting me in creating a paper that can be more appealing to read by removing excessive repetition of words.

Some drawbacks of ChatGPT are that it can still provide inaccurate information therefore it cannot be entirely relied on for research purposes. For example, when I asked it what the input voltage is for the ULN 2003, it told be the range is about 6V to 15V, but to reference the datasheet for this information. While it telling me to use the datasheet is a good thing, it still ended up providing me a number which proved to be incorrect when looking at the datasheet. Depending on the version of ChatGPT used, it has varying levels of browsing capabilities to allow for it to have access to additional information. An additional drawback is the fact that with having a source like this so easily accessible, it creates the temptation to use it for purposes



which display a lack of integrity. There is essentially no limit on the types of questions which can be asked to it because there are round about ways to ask it particular questions. One could for example, choose to have ChatGPT write paragraphs for it simply by providing it with some information and asking it to make something longer, or to add more details to it, thus stopping an individual from doing their own work. Additionally, when using and relying on ChatGPT to do something like this, it often can only rely on the information that was given to it in the prompt, thus creating a redundant paragraph with lots of excess words that actually provide no real substance to the paragraph.

## 6 HARDWARE SYSTEM DESIGN

The project includes a PCB with many components such as MCU, regulators, and motor controllers. This section will go over the software selection for the PCB design as well as the circuitry.

### 6.1 POWER DELIVERY

To power each of our main components, we will need three regulators. Each design was picked in the core component selection section above. These three regulators will be on a custom design PCB board along with other components that will be explained in the next couple sessions.

Within the regulator designs, there are three other features along with the voltage regulation.

#### 6.1.1 SWITCH

Right at the beginning of each regulator circuit there will be a switch. The main purpose of this component will be the ability to isolate each of the circuits by individually turning them off as needed. This can be helpful for testing purposes as well as emergency shutdowns.

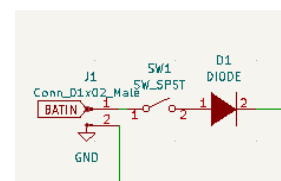


Figure 6.1 Switch Schematic

#### 6.1.2 DIODE

The diode will come right after the switch. Its main purpose is to protect the battery from reverse polarity. Some of the benefits of doing this is so that if the circuit is connected in the opposite polarity, it would cause no damage to either the battery or the components in the PCB. One of the drawbacks of this method is that it introduces a voltage drop to the circuit. This means that it would lose some of the efficiency by reducing the incoming voltage before it reaches the regulator. To reduce this inefficiency, a diode with low voltage drop will be chosen.

#### 6.1.3 EMERGENCY STOP

This switch will serve the purpose of shutting down the system in case of emergency.

#### 6.1.4 LED

At the output of the regulator, there will be a circuit with the purpose of indicating whether there is voltage going through the regulator. A LED and a resistor will be connected in series to each other and in parallel to the regulator's output. To find the value for the resistor, find the voltage drop of it by subtracting the LED voltage drop from the output voltage of the regulator and divide it by the current going through the LED. For example, for the regulator with the 5V output, the LED has a 3.3 voltage drop and 0.02A. The resistor value will be  $(5 - 3.3)/0.02 = 84$  Ohms. The same calculation was made for all of the other regulators.

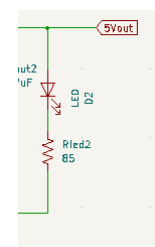


Figure 6.2 LED Schematic



### 6.1.5 12V TO 7V

This regulator will be wired to the node between the two batteries and will supply the Arduino MEGA 2560 Rev3.

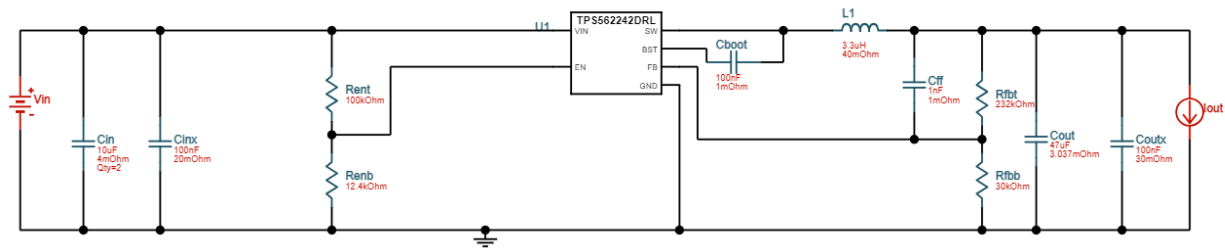


Figure 6.3 Arduino Mega 2560 Regulator Schematic

### 6.1.6 12 TO 5V

This regulator will be wired to the node between the two batteries and will supply the Libre Computer Le Potato Pi.

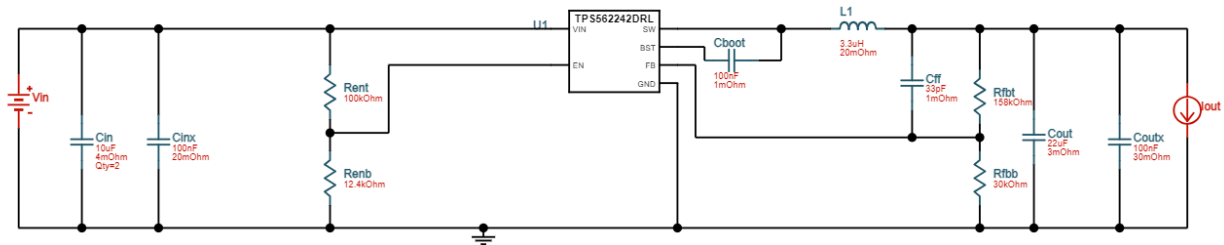


Figure 6.4 Le Potato Pi Regulator Schematic

## 6.2 MOTOR CONTROLS

### 6.2.1 STEPPER DRIVERS SCHEMATIC

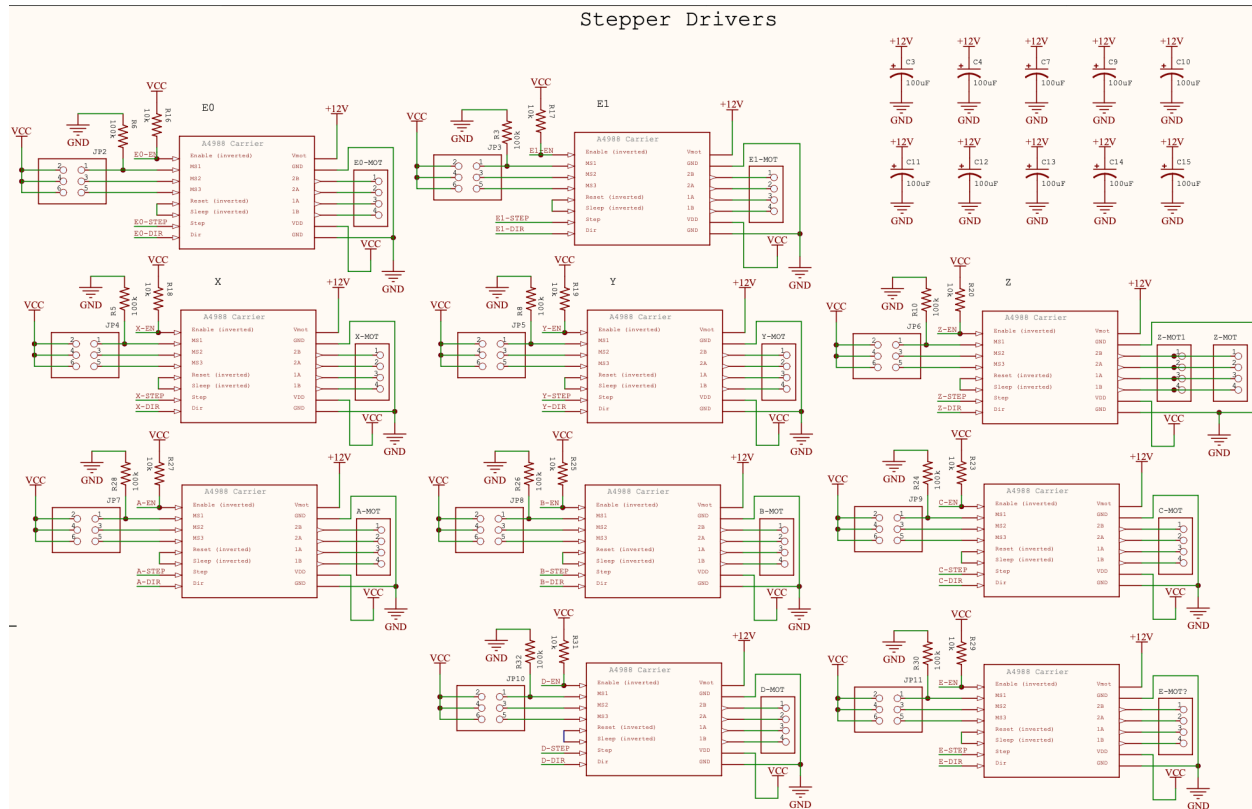


Figure 6.5 Stepper Drivers Schematic

Here we have the schematics for the A4988 carrier where our motor drivers would be connected to the board, additionally, we have the connectors for the wiring between the motor and the board to allow for interfacing with the motor drivers. These carriers are based on the carriers which existed in the original RAMPS 1.4 schematic, while these could be updated to be specific DRV8825 carriers, it is not needed because like stated earlier, these A4988 carriers are able to have DRV8825 carriers connected directly to them.

### 6.2.2 POWER AND RESET

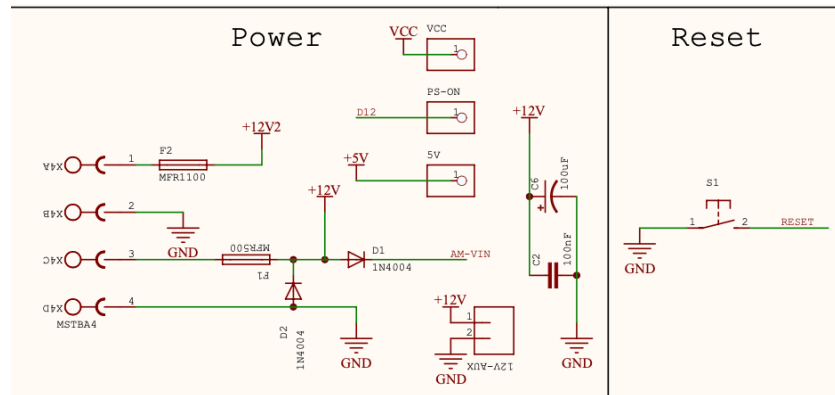


Figure 6.6 Power and Reset Schematics

These schematic shows the connection to the power source and ground and the voltage that is being fed through these connections. Additionally, the diode exists to control the voltage that is fed to the Arduino. There is also the reset switch, serving as a reset for the board.

### 6.2.3 ARDUINO MEGA CONNECTIONS

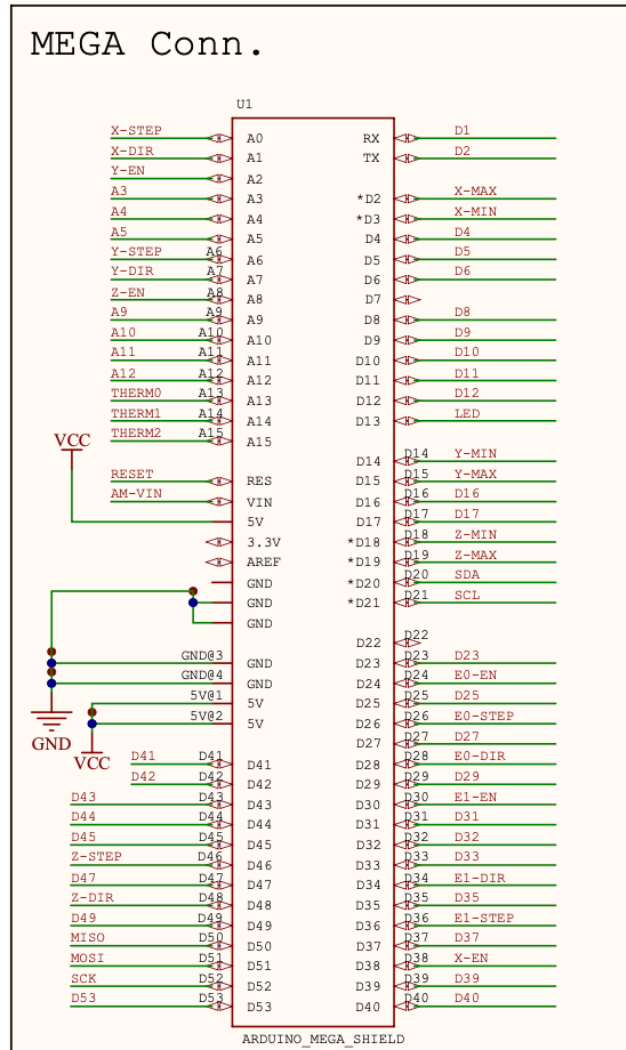


Figure 6.7 Arduino Mega Pinout Schematic

This shows all the connections which are on the RAMPs 1.4 board and allows for it to be connected to the Arduino, additionally we can see all the pin labels for the pinout of the Mega when used in this application.

### 6.2.4 LED AND ENDSTOPS

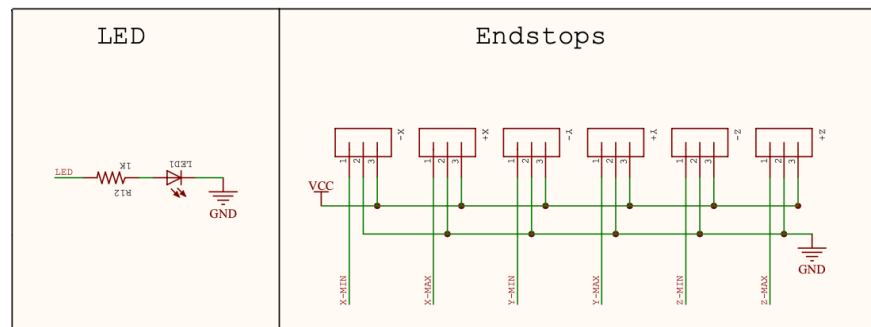


Figure 6.8 LED and Endstops Schematics

The LED exists as an indicator of connectivity of the board and the endstops help to limit the directions of the X, Y, and Z motors if necessary.

### 6.2.5 THERMISTORS AND I2C

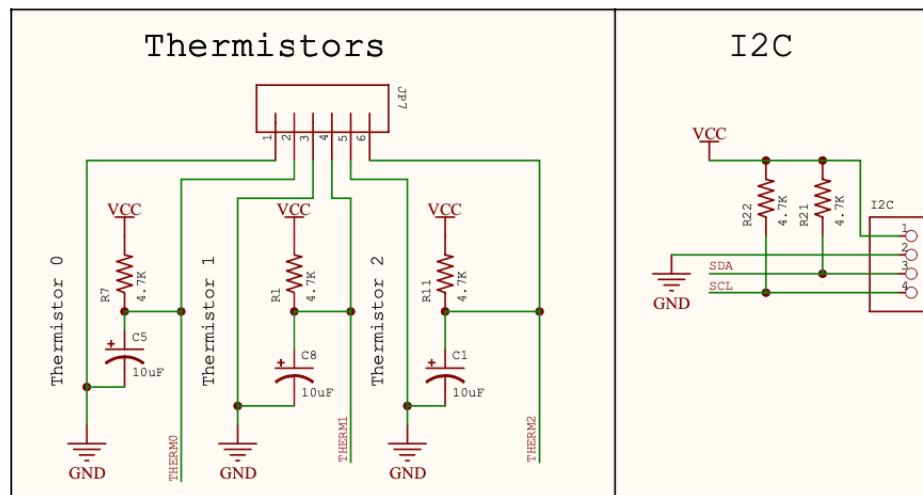
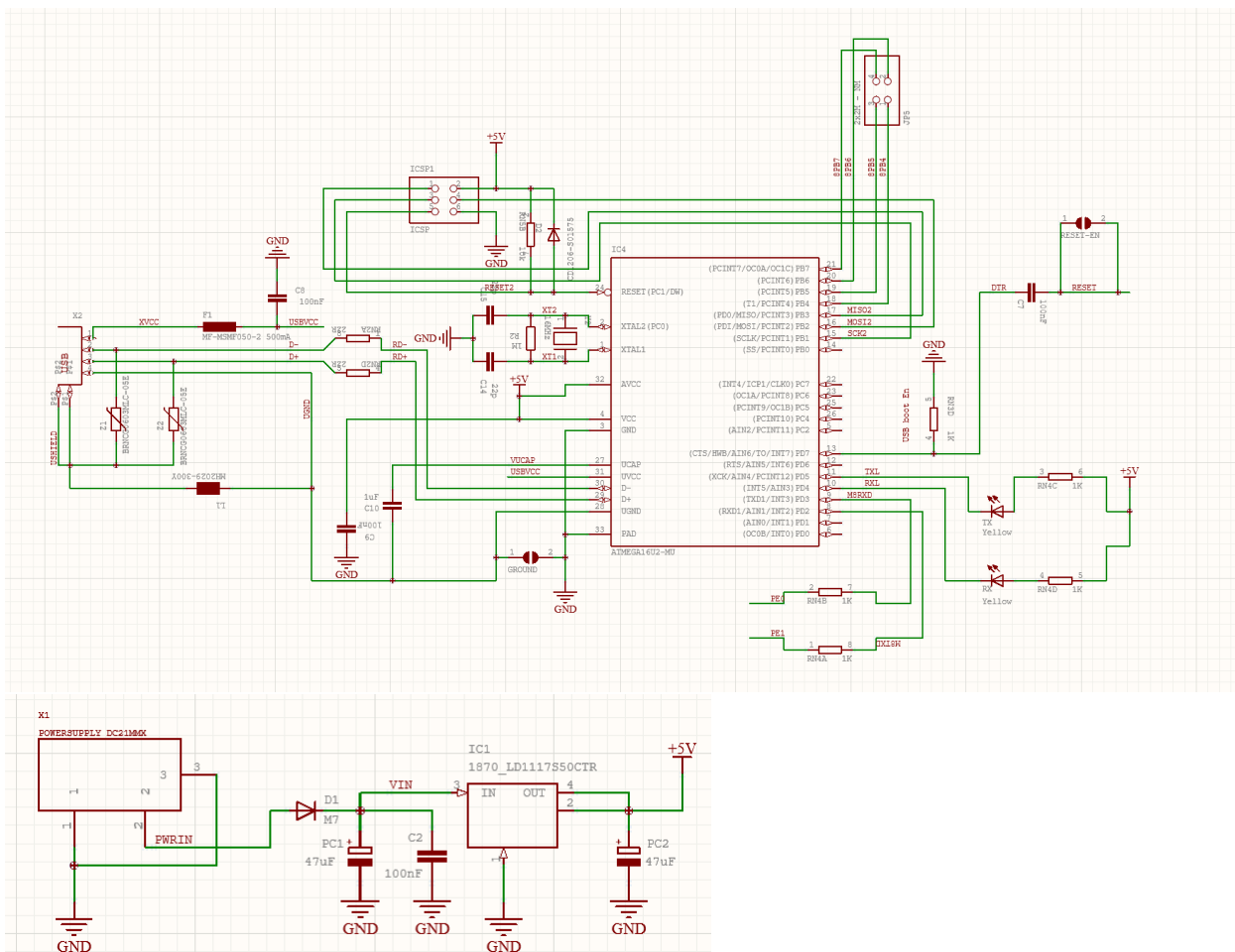
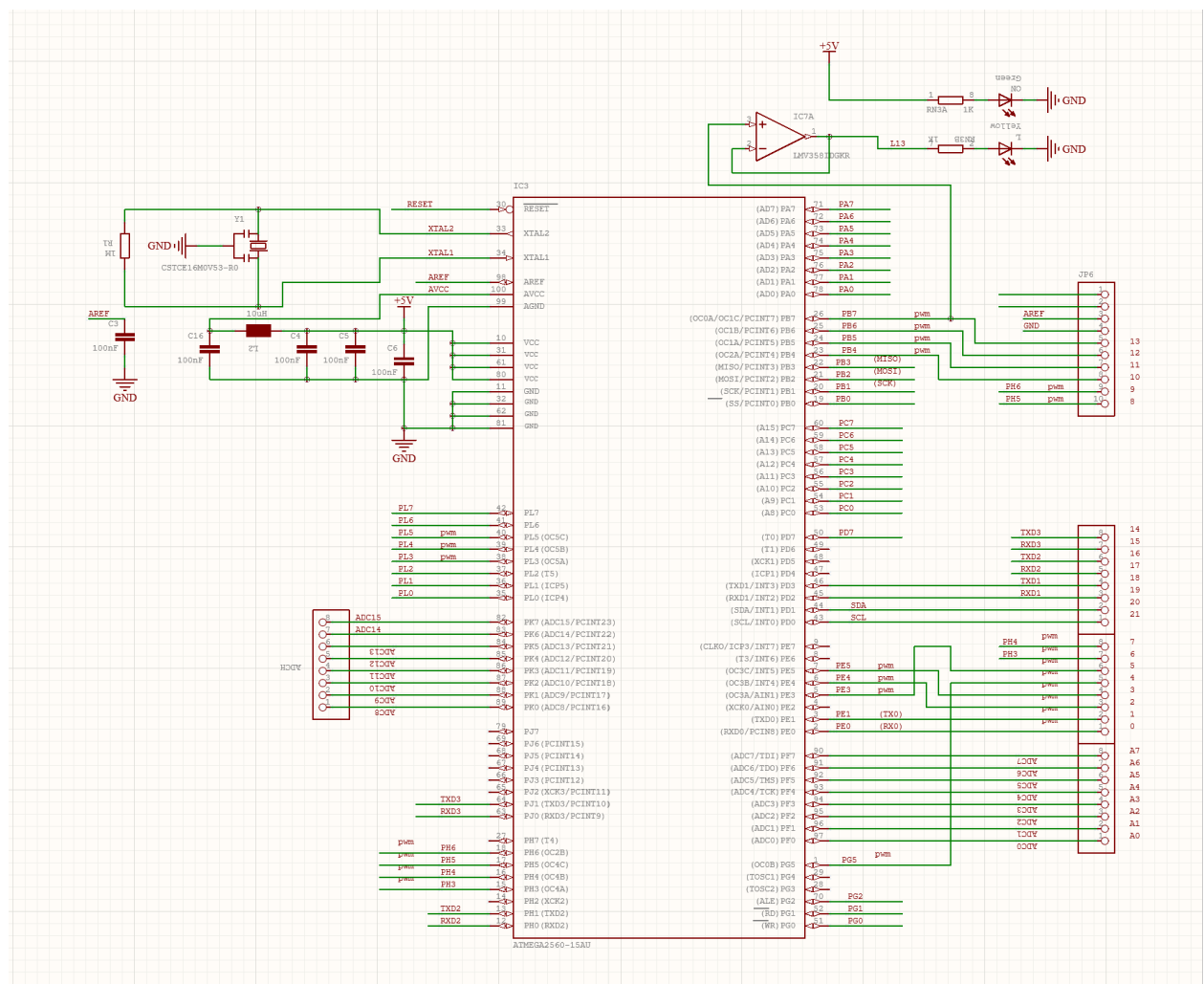


Figure 6.9 Thermistors and I2C Schematics

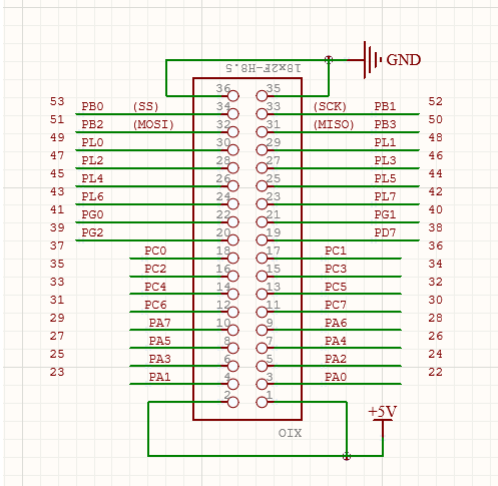
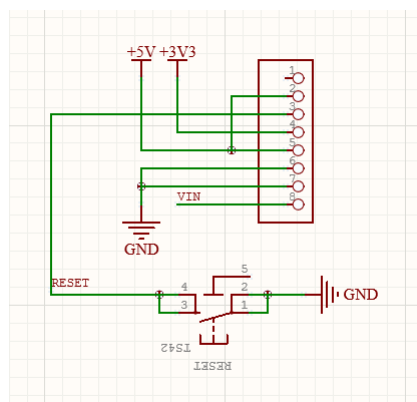
The thermistor connections are used to connect to sensors which are used to monitor temperatures of desired components and the I2C connection exists should I2C be desired for any applications.

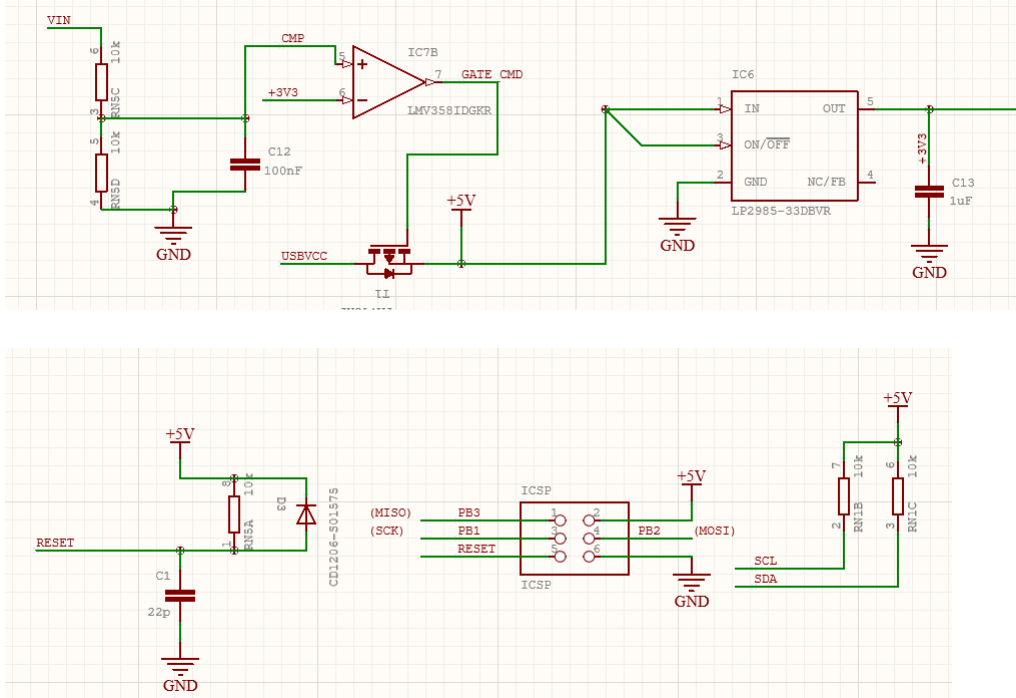
## 6.3 MICROCONTROLLER DESIGN





Caption

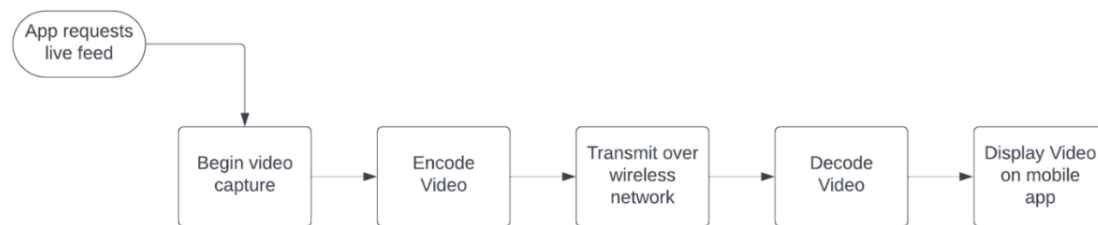




## 7 SOFTWARE SYSTEM DESIGN

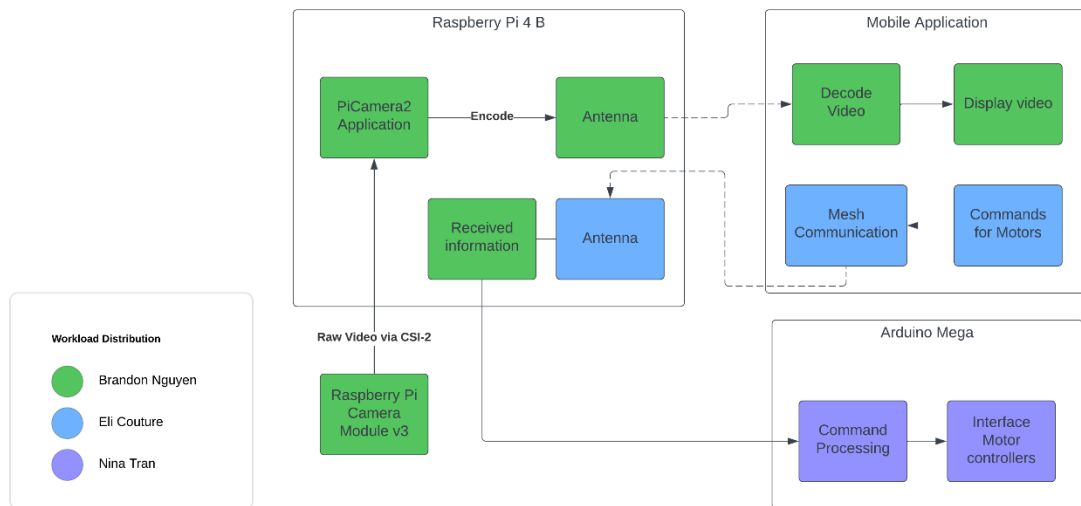
### 7.1 CAMERA SYSTEM SOFTWARE

In order to save bandwidth on the wireless network between the mobile application and the rover, it is important that video data is only being sent when the application is able to process the data and view it. In other words, if the operator isn't viewing the page with the video feed on the mobile app, then we shouldn't try to capture and send video then. The solution to this issue would be to design the software system in a way that allows for the mobile application to communicate to the microcontroller that it would like to now begin receiving video data and thus prompt the microcontroller to begin capturing video and encoding the data to be sent over the wireless network. The following diagram below demonstrates the basic control flow of the video capture and transmission process.



*Figure 7.1 Video Transmission Process Flowchart*

The following software block diagram highlights which components in the project will be responsible for which task of the video transmission process as well as other data within the rover system.



*Figure 7.2 Software Block Diagram*

The structure of the embedded application will depend on the software library used to interface with the Arducam IMX708 USB Camera Module 3. There are two options available: the open-source Libcamera library and Raspberry Pi’s proprietary Picamera2 library.

#### 7.1.1 PICAMERA2 LIBRARY

The Picamera2 Library is written based on the libcamera library in Python and designed for Raspberry Pi Cameras as the name ensues. The Picamera2 library directly uses the bindings found in the libcamera library while providing higher level API for greater ease of use that is created specifically for Raspberry Pi cameras. The library is designed for systems running either Raspberry Pi OS version or Raspberry Pi OS Lite and is typically pre-installed in current images of the OS downloaded from the Raspberry Pi website, according to the library manual. Picamera can also operate in a headless manner, meaning that it does not require an attached screen or keyboard to function properly, which greatly suits this project’s need to send video data remotely. Since the Picamera2 library is built on top of the open source libcamera library, there may be no need to work with the libcamera library directly to avoid unnecessary costs in “reinventing the wheel” by not taking advantage of the high-level APIs offered by Picamera2.

##### 7.1.1.1 COMMONLY USED PICAMERA2 DEPENDENCIES

###### 7.1.1.1.1 OPENCV

OpenCV is an open-source library with a vast amount of computer vision algorithms organized in several modules sorted by their application. There is a “core functionality” module that is used to define the library’s basic data structures that are used by all the other modules. The auxiliary modules are designed for the following applications: image processing, video analysis, 3D, 2D features frameworks, object detection, camera calibration, stereo correspondence, high-level GUI, and video I/O.

###### 7.1.1.1.2 TENSORFLOW LITE

TensorFlow Lite is a lightweight version of the open-source machine learning framework TensorFlow, designed for mobile and embedded devices. Its key features include multi-



platform support (covering Android and iOS devices, embedded Linux, and microcontrollers), diverse language support (including Java, Swift, Objective-C, C++, and Python), high performance through hardware acceleration and model optimization, and end-to-end examples for common machine learning tasks. Due to the constraints of this project, it is unlikely that machine learning image processing will be done on the live video feed and therefore TensorFlow Lite will not likely be useful for the purposes of this project. Although, it would be a good place for growth in expansion on this project.

#### 7.1.1.1.3 FFMPEG

FFmpeg is an open-source software project that provides a collection of libraries and tools for processing multimedia data like audio and video. It can perform video and audio encoding, decoding, transcoding, streaming, and more. While video and audio encoding, decoding, and streaming are the most pertinent features relating to this project, FFMpeg is also capable of format conversion, video and audio manipulation (cropping, resizing, etc.), basic editing, recording, and applying filters and effects. It is probable that this package will be used in the embedded application for streaming the live video in this project.

### 7.1.2 LIBCAMERA LIBRARY

The open source libcamera API library is what the Picamera2 API library is built on top of. It provides a hardware-agnostic way of interfacing cameras on Linux based systems and streamlines development by abstracting hardware complexities, unifying APIs across different manufacturers, and managing the camera pipeline and configurations. While the libcamera library presents itself as a unified API, it is made up of several components consisting of Camera Devices Manager and Camera Device objects that access the lower-level Helper and Support classes. The Camera Device object represents a camera device to the upper layer in the program and is instantiated by the Camera Devices Manager. The Camera Device consists of both device-agnostic functions and device-specific image processing algorithms and a (device-specific) pipeline handler. The helper and support classes consist of MC and V4L2 support, buffer allocators, sandboxing IPC, plugins manager, and the pipeline runner, among other functions as well. Given that the Picamera2 library is built on top of the libcamera library, there is no reason to work with the libcamera library directly as it seems to be too low-level to be feasible to work with given the time constraints of this project.

### 7.1.3 PICAMERA2 API FUNCTIONALITIES OF INTEREST

Given the vast possibilities of applications available for the use of microcontroller cameras, the Picamera2 library has many features that will have great practical use for this project and others that may prove to be unnecessary or too niche for this project. This section will discuss the most important features of the Picamera2 API library and their implications for the project.

#### 7.1.3.1 AUTOFOCUS AND CAMERA CONTROLS

Autofocus is one of the many camera controls that can be changed at runtime. Generally, camera controls can be set at three different times: in the camera configuration, after configuration but before the camera starts, and after the camera has started. The availability of the autofocus control depends on the hardware; if the camera module does not support autofocus, then changes to that control will fail.

Autofocus within the Picamera2 is a state machine with three states: manual, auto, and continuous.

The manual focus mode puts the camera in a state in which the lens will never move spontaneously, but the lens can be adjusted manually by using the “LensPosition” control whose units are in dioptries.

The auto focus mode also does not allow the lens to move spontaneously, but moves in response to a written application and using the “AfTrigger” control to start an autofocus cycle. The “AfState” metadata can be used to determine whether the lens was successfully focused.

The continuous mode represents autofocus in the most conventional sense where an autofocus algorithm runs continuously to refocus the lens spontaneously whenever necessary.

Setting the focus mode for the camera on Picamera2 is as simple as calling the “set\_controls()” method from the Picamera2() object. There are other controls related to autofocus including “AfRange”, “AfSpeed”, “AfMetering”, and “AfWindows”. AfRange allows one to adjust the focal distances that the algorithm searches. AfSpeed allows the user to adjust the autofocus algorithm to run at a faster or slower rate. AfMetering and AfWindows allows the user to change the area of the image being used for focus.

#### 7.1.3.2 ENCODERS AND OUTPUT

The video encoder is used to determine the amount of compression of the video output by either supplying a quality parameter or a bitrate parameter to the encoder.

There are four encoder types in the library:

1. H264 Encoder
2. Jpeg Encoder
3. MJPEG Encoder
4. “Null” Encoder

The H.264 encoder uses the Pi’s hardware through the V4L2 kernel drivers supporting up to 1080p30 output. The encoder supports three optional parameters: bitrate, repeat, and iperiod. The H.264 encoder can accept either 3-channel RGB, 4-channel RGBA, or YUV420 color formats. The Jpeg encoder is a multi-threaded software encoder which can be used as an MPEG encoder with the option of selecting the number of concurrent threads to use for encoding, quality, color space, and color subsampling. This encoder cannot use any YUV formats.

The MJPEG encoder is another hardware-based encoder that utilizes the Raspberry Pi’s built-in hardware accessed through the V4L2 kernel drivers. Only bitrate can be modified with this encoder and the encoder accepts either 3-channel RGB, 4-channel RGBA, or YUV420.

The “Null” encoder is essentially an encoder that does nothing at all and outputs the same frames that were passed to it without doing any compression or processing.

There are three kinds of outputs available for use in the Picamera2 library.

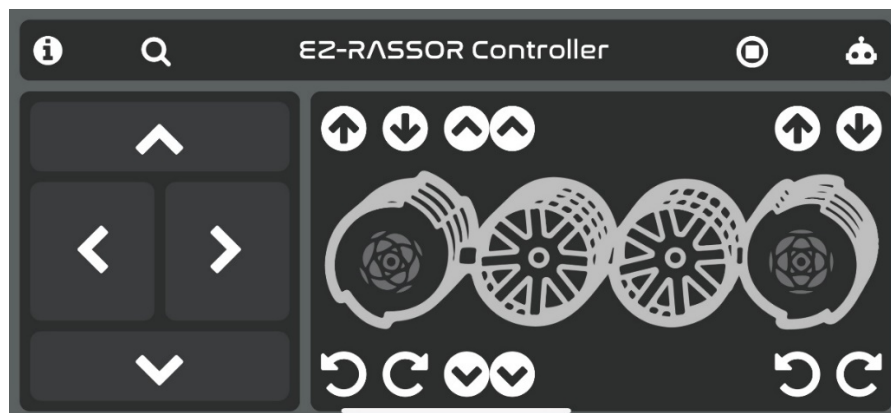
1. FileOutput
2. FfmpegOutput
3. CircularOutput

### 7.1.3.3 STREAMING TO A NETWORK

The Picamera2 API is capable of three streaming modalities: streaming to a TCP socket, streaming to a UDP socket, and streaming MJPEG video to a webpage using a simple webserver. If streaming video data directly from the rover system to the mobile application is not possible, it may be desirable to then use a simple webserver to store the video data and have the mobile application request the data. Ideally, the video data would be sent to a local webserver that exists solely on the local area network on which the mobile application and rover is connected to avoid latency and issues with using a remotely hosted server that would require internet access (Wide Area Network), which would not be ideal working as a proof of concept for a lunar exploration system where internet access may not be feasible or readily available.

## 7.2 USER INTERFACE

The user interface of the mobile application used to view the camera feed and remotely control the rover's motor functions is built on top of FSI's pre-existing mobile application from the EZRASSOR-Cart repository (which is also based on the EZRASSOR-Control repository). The image below depicts the current state of the user interface of FSI's current mobile application.



*Figure 7.3 Mobile Application Main Screen UI*

The pre-existing user interface as in Figure x. shows arrows in the left-hand window which will be used to direct how the motors connected to the wheels of the rover should rotate. There is plenty of space left in the header of the interface to add buttons to go to new pages such as a signal statistics page and the mesh file sharing system page. The window on the right-hand side of this main page has been shown to be non-functional in its current state of development so there is the option of implementing the live camera feed onto this main page and/or delegating that function to a page of its own.

Additional user interface pages will have to be developed either on top of or independently for the mesh network message-sharing subsystem of the rover, providing file transfer status, signal status, and node availability. The following figure depicts a rough draft of what such a page could look like.

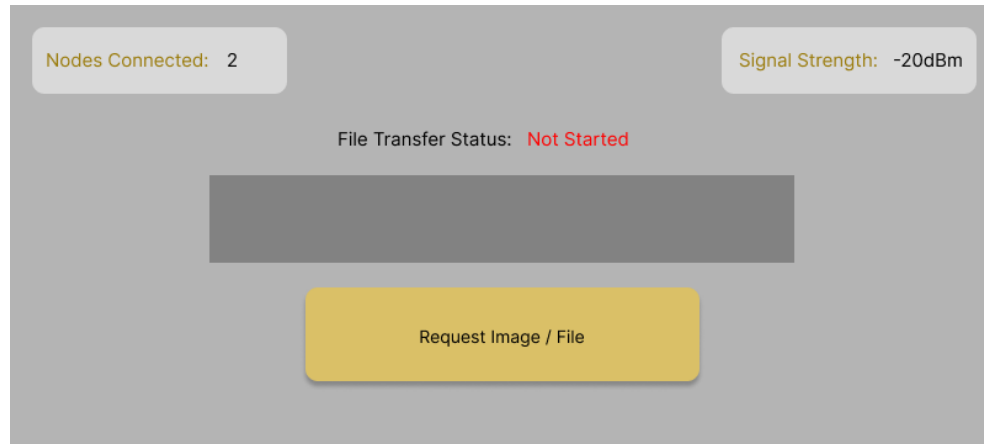


Figure 7.4 Mesh Networking Subsystem UI Draft

### 7.3 USE CASE DIAGRAM

The following figure summarizes the overall functionality of the mobile application and how it interacts with the rover, the mesh network, and the web-service. The “establish connection” process represents the process by which the user and the rover must be on the same local area network in order to use the mobile application. From there, there are four main functions in the mobile application: viewing the live camera feed, sending motor control commands, viewing the signal status of either the Wi-Fi or Zigbee mesh networking signal, and requesting/viewing files which will be images for the demonstration.

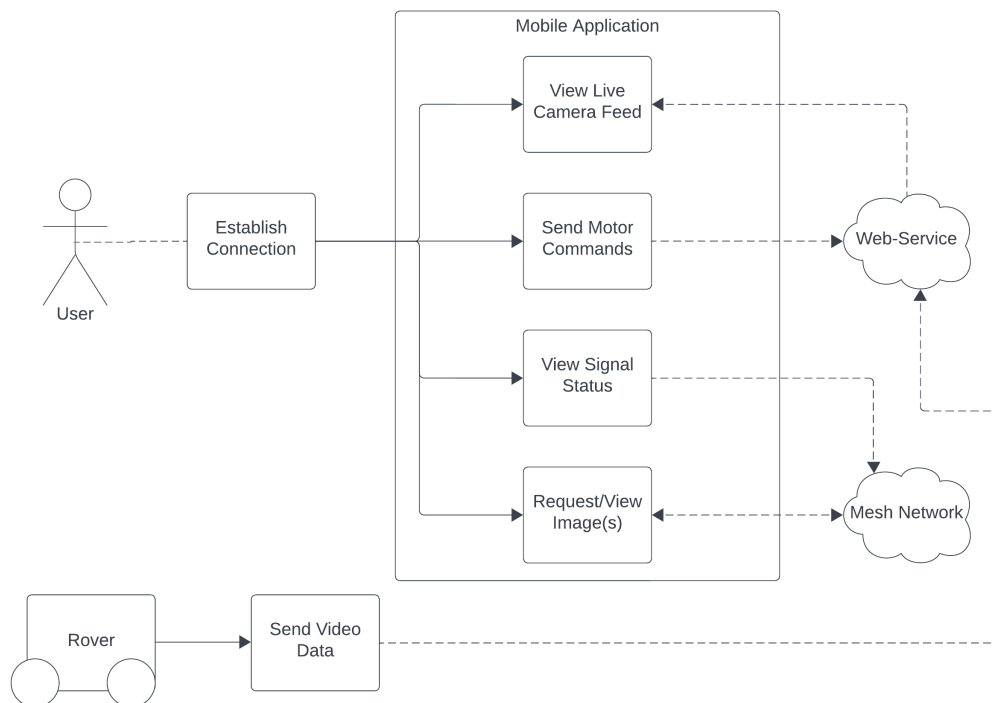


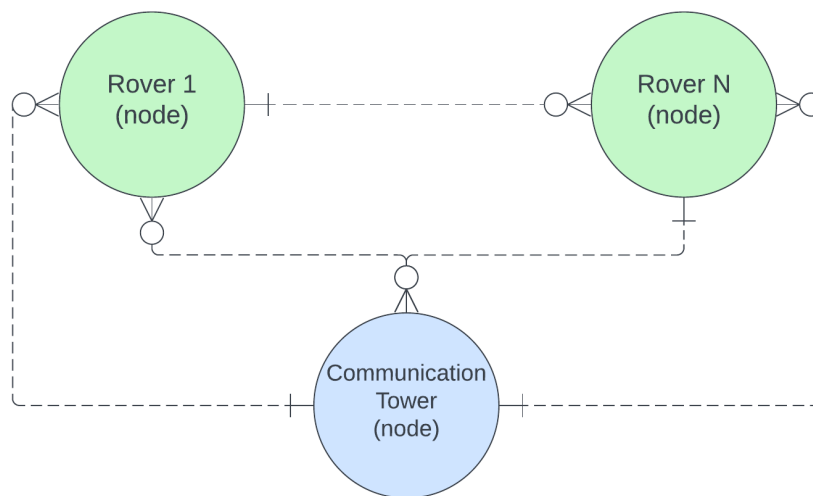
Figure 7.5 Mobile Application Use Case Diagram

#### 7.4 SOFTWARE VERSION CONTROL

The choice for software version control is straightforward: Git and GitHub will be used to manage the development and organization of existing and new software components. Effective utilization of these tools will allow for smoother integration of our team's original software design into FSI's pre-existing code base and a smoother debugging process by ensuring that working versions of code are untouched while experimental code is managed within separate branches of working code. Once experimental code is tested and verified for functionality, it can be merged into the main branches for deployment.

#### 7.5 COMMUNICATION NETWORK DIAGRAM

The mesh communication network in this project seeks to incorporate transfer of files and images through the Zigbee wireless communication standard. Viable nodes for the mesh network would include the rover in this project and a communication tower being developed in another project at Florida Space Institute. These nodes will be capable of two-way communication and data transfer and can use intermediary nodes to reach another if one node is out of range for an adequate signal. The diagram below depicts the relationship between these nodes.



*Figure 7.6 Mesh Network Entity Relationship Diagram*

Each node, whether it is a communication tower or a rover, has a one-to-many relationship between other N nodes.

#### 7.6 DATAFLOW

Information processing in this project will consist of receiving data from two sources: the mobile application sending motor control commands and the camera connected to the Le Potato Pi Mini which is part of the rover system itself. With that established, the Le Potato Pi Mini will be the main point of connection between the rover system and the mobile application and will therefore receive motor control commands from the mobile application and relay it to the Arduino Mega microcontroller to process and execute the commands on the motor controllers. The Le Potato Pi Mini will also transmit information such as remaining battery life, video data, and other important

information to be displayed on the mobile application. Figure (x) from Section summarizes the flow of the various data in the system.

Since the Arduino Mega and the Le Potato Pi Mini will both be housed within the same electronic components box, the two microcontrollers can be wired to one another to communicate via one of the three following communication interfaces: I2C (Inter-Integrated Circuit), SPI (Serial Peripheral Interface), or UART (Universal Asynchronous Receiver-Transmitter).

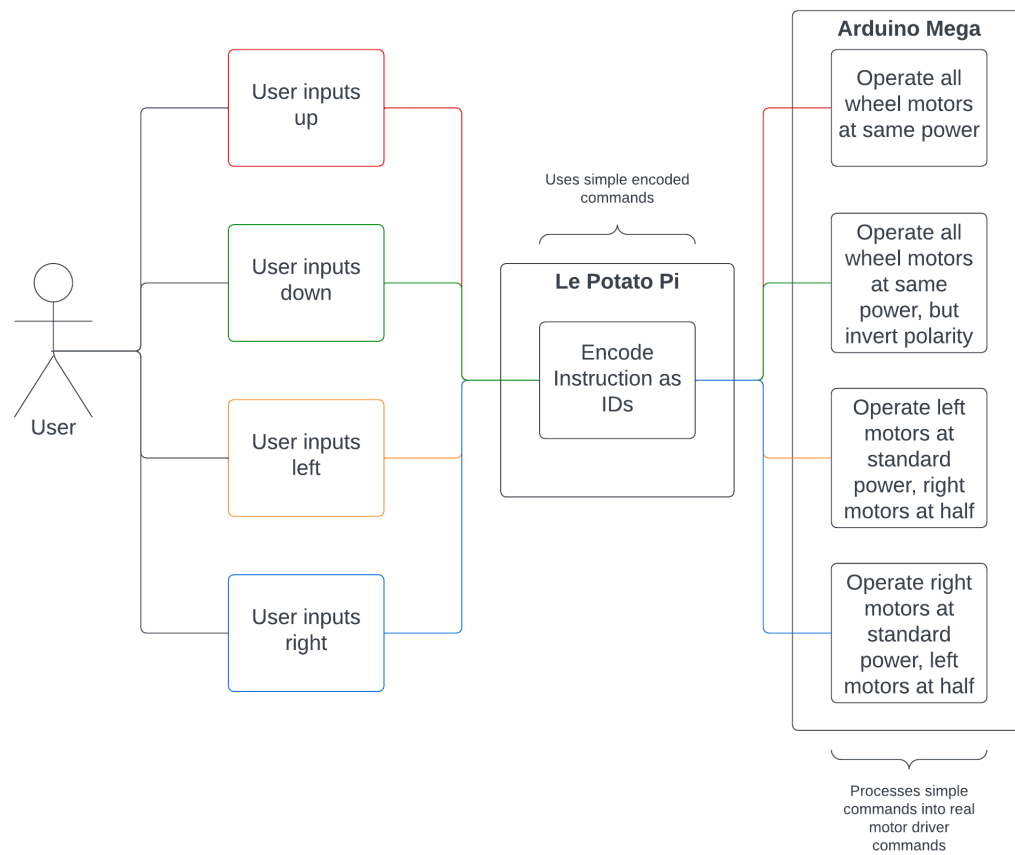
I2C provides a two-wire interface that supports multiple devices and is optimal for short-distance communication. SPI supports higher-speed communication over short distances similar to the I2C interface. UART provides straightforward point-to-point communication between microcontrollers only requiring two wires, one for transmission and one wire for reception of data, providing a simple implementation.

Since communication of motor controls will simply be between the Le Potato Pi Mini and the Arduino, UART will be the optimal interface to implement simple transfer of motor control instructions. The other interfaces, I2C and SPI interfaces simply offer too many unnecessary features that do not justify their more complex implementations. SPI offers the highest data rates at the expense of using 4 wires to implement. Both SPI and I2C offer multi-device support through connecting them on the same bus, but this feature is unnecessary since these communication interfaces will be used only between the two microcontrollers. The following table summarizes this comparison between communication interfaces.

*Table 7.1 Inter-Microcontroller Device Communication Interface Comparison*

Communication Interface	UART	I2C	SPI
Maximum Data Rate	~5 Mbps	100 kbps - 3.4Mbps	60 Mbps
# of Wires	2	2	4
Relative Effective Distance	Long	Short	Short
Multi-device Support	No	Yes	Yes

The following figure demonstrates the dataflow for how the motor commands will move from the user's input on the mobile application to responsive movement on the rover. The exact mechanics behind how the application will command the motors to cause the rover to turn left or right is in a preliminary state and may change with testing, but the overall structure of the data flow between the microcontrollers passing instructions will remain the same.



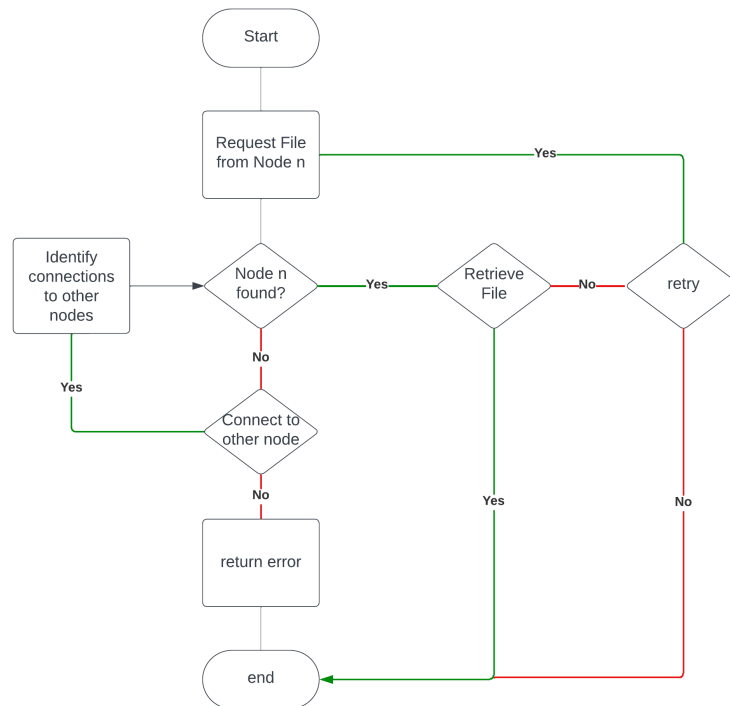
*Figure 7.7 Motor Control Use Case Diagram*

The interface by which the mobile application, Le Potato Pi, and Arduino will communicate is through a software library called the Robot Operating System, or ROS for short. The teams at the Florida Space Institute have built their communications on this framework and so it would be advantageous for both parties, our senior design team and future team members at the Florida Space Institute to work within this framework to not only avoid “reinventing the wheel” by redoing work that has already been done but showing that additional functionality can be added on. Although ROS2 will be used across all of the project’s platforms, between the Le Potato Pi and the Arduino, the communication medium will still be through UART and the Le Potato Pi and the mobile application through a local area network.

### 7.7 MESH NETWORK STATE DIAGRAM

The rover mesh network will deploy a file sharing system that will have some fault-tolerance through the use of timeouts, allowing the user to retry a file transfer, and recognizing when a node is unable to be found.

The following figure demonstrates the various states of the mesh network subsystem application. Note that the terminating states are when the file is successfully retrieved, an error is returned (indicating that no nodes are in range), and when a retry for a file transfer is refused.



*Figure 7.8 Mesh Network State Diagram*

## 8 SYSTEM FABRICATION

### 8.1 PCB DESIGN SOFTWARE

Our group will use the same PCB design software. This is important to maintain consistency between the PCB design of each of our group members. Some of the most popular software are EAGLE, EasyEDA, KiCad, and Altium.

#### 8.1.1 EAGLE

Eagle has a very user-friendly interface, which can be helpful considering members of our group have used different software for PCB design. This is also the software we use in the Junior Design course, offered before Senior Design to introduce the topic of PCB design. EAGLE has a wide library of components, and it is free software for students.

#### 8.1.2 EASYEDA

The main feature of this software is the collaboration features. This could help our group by allowing multiple members of the group to use the same file to build our design. One of the drawbacks of this software is that there is a dependency on the internet. Because of the cloud storage and collaboration feature, the software is heavily reliant on internet usage. The offline version of the software has much less features.

#### 8.1.3 KICAD

One of the most important features of KiCad relative to this project is that there are no limitations to the board size or layer count. Considering that our PCB will have many components and may come out quite large, this feature is helpful. When using one of the other software, we run the risk



of reaching our limit of size or layers, which could lead to having to switch the software we are using. The 3D modeling capabilities of KiCad may not be as advanced as the ones from other software, but that feature is not a high priority for this project.

#### 8.1.4 ALTIUM

Altium is one of the most widely used PCB design software, which is valuable to us as there is likely to be more resources if we run into issues. It provides a large online component database which allows for quick downloads of a desired component to add into our schematics and PCB design. While typically expensive to download, there is a free license available to students making it a viable option for usage with our project. There is also the option of online collaboration when using Altium. In comparison to the EAGLE version, we have available to us, there is a major advantage of having a much larger board size and greater signal and plane layer allowance.

#### 8.1.5 PCB SOFTWARE DECISION

For this project, our final decision is to use Altium because we can use it at no cost to us and it outshines the other programs in the greater flexibility when it comes to size of design. Even though, we likely won't max out on our design both in size and complexity, having the ability to do that allows for a reduction of concerns in our PCB design.

### 8.2 PCB DESIGN PHILOSOPHY

PCB are used to incorporate components of a circuit into one design on a board rather than using something like a breadboard which has much more room for error due to loose connections. A schematic is converted into a design on a PCB which is realized through copper traces, pads, and conductive planes. There are multiple layers on a PCB, with the layers of conductors being separate by insulating layers, additionally there is a solder mask around the board and a silkscreen to provide labels. Additional components can be mounted on the surface of the board.

When referring to layers of a PCB, these are typically referred to as the copper layers on the board. The copper layers can be made thinner or thicker depending on the needs of the design, as designs with higher voltages, resistances, or impedances may require a thicker copper layer. There are substrate layers in the PCB as well which are usually fiberglass which can provide rigidity to the PCB. While there are various substrates which can be used, one of the most widely used ones is FR-4. A solder mask which is a thin layer of polymer encases all this, which is a protective measure for the PCB as it protects the copper and is a protective measure for soldering to stop it from spreading to other pads. The silkscreen is used to provide labels which allow for the identifying connections or components, making connecting the PCB much more user friendly. These can also often house a company logo or product name to allow for identification of the PCB.

#### 8.2.1 RELIABLE PCB DESIGN PRACTICES

As the design of our PCB is a very important factor in our project and PCB design as a whole is a crucial portion of today's technology, it critical to follow reliable PCB design practices. There are certain rules that should be followed to ensure we develop a working PCB which we can rely on for application in our project.

### **Component and Circuit Placement**

Individual passive components should be arranged in a way that reduces the length of a conducting trace, to allow for reduce inductance and noise in the signal being carried through the trace. Additionally, if the PCB must hold to dimensions, strategically placing these components will allow for maximizing the usual space on the PCB while still upholding to any size restrictions. Subcircuits on the PCB should also be kept together on different areas to again minimize trace length. Heat dissipation should be considered in these circuits as well, because if one circuit contains heat sensitive components, if it is possible, they should be placed far away from a circuit which might generate more heat than normal. Power supply connections and input/output connections should also be placed near the edges, if possible, just to allow for a more logical design.

### **Power and Ground Planes**

Using power and ground planes are also ideal because this reduces the need for ground or power traces which can make the PCB design simpler. Additionally, with using a power plane, the current carrying capacity is increased because traces have a limit to the current they can carry. Vias are used to direct power to the signal layer when using a plane.

### **Review Design**

Although this may seem like an obvious rule to follow, it is an important one to highlight because not reviewing design can lead to time and money wasted by having a board produced which does not pass basic checks. Altium has design rule checking and electrical rule checking, the former of which can check the logical and physical integrity of a design. It can check minimum clearance rules as well as other design rules to ensure nothing is violated. The latter on Altium is able to, as the name implies, verify that electrical rules are not being violated, including with components, documents, or nets.

## **8.3 ENCLOSURE DESIGN**

The enclosure design for our PCB is within the electrical box of the rover. There is an additional box in which the current RAMPS board and Le Potato can be slid into which separates it from the battery and allows for wires to be run throughout the rover, to connect to both the battery and the motors. This is intended to shield the electronics from outside exposure and keep the PCB in a stable position when the rover is moving.

## **9 PROTOTYPE SYSTEM TESTING**

### **9.1 PROTOTYPE HARDWARE TESTING**

#### **9.1.1 TEST PLAN FOR RAMPS BOARD**

The prototype hardware testing for the RAMPS board encompasses the majority of the hardware components to allow for functionality of the movement in the rover. The goal is to evaluate functionality of the parts which will be interfaced with the PCB when it arrives. Additionally, we want to see if we can get the desired functionality with the RAMPS board at the increased voltage to see how this will affect the peripherals of the board.

The components include:

- ☐ NEMA 17 motors
- ☐ DRV8825
- ☐ RAMPS 1.4

- Arduino Mega 2560 microcontroller

Our plan is to hook up the NEMA 17 motors to the RAMPS board with our DRV8825 drivers connected and power this with 12 volts first, thus the plan is to implement the current configuration of the rover. Next, we will complete modifications to our board, which will allow for the board to be powered with 24V, thus verifying that all peripherals are able to operate at this voltage as well. We will attach one of the rover wheels to our NEMA 17 and implement a simple stepper motor test code to verify that we have the ability to have our motor move the wheel.

### 9.1.2 TEST PLAN FOR LE POTATO PI

The initial plan for testing the Le Potato Pi from a hardware standpoint is to connect all necessary peripherals and a display output resembling the maximum standard workload for the microcontroller. Acceptable performance would be described through stability of the operating system (no kernel failures, no file system errors) and power stability (no spontaneous reboots, status LEDs are properly powered).

## 9.2 PROTOTYPE SOFTWARE TESTING

The overall philosophy for the prototype software used for testing the individual components will entail creating various minimal applications to simply evaluate the functionality of the various components of the rover system.

These components include:

- Le Potato Pi microcontroller
- Arduino Mega 2560 microcontroller
- Arducam IMX708 camera module
- NEMA 17 and NEMA 23 motors
- Zigbee USB module

### 9.2.1 TEST PLAN FOR LE POTATO PI MICROCONTROLLER

The test plan for the Le Potato Pi microcontroller software will be to successfully create and run an image of the latest version of Ubuntu on the microcontroller and host the test applications for the Arducam IMX708 camera module and the Zigbee USB module. Functionality is verified if the Le Potato Pi microcontroller is able to run both test applications simultaneously.

The desktop image of Ubuntu 22.04.3 was flashed onto a microSD card using Win32DiskImager.

### 9.2.2 TEST PLAN FOR ARDUINO MEGA 2560 AND MOTORS

For the purposes of testing and demonstrating the functionality of the peripherals used on the Arduino, a development kit will be used as a base for the RAMPS board that will power the motors. The test plan for the Arduino microcontroller and the motors that it controls will be to create a simple application that sends simple commands to drive the motors and/or flash the existing motor control code developed at FSI to test the functionality of the Arduino and the motors. Functionality is verified if the motors responds as intended according to the commands sent.

### 9.2.3 TEST PLAN FOR ARDUCAM IMX708

The test plan for the Arducam IMX708 camera module will be to write a simple application that displays the camera's output to a monitor via HDMI. Standard USB UVC drivers will be used to interface the camera as pre-installed with the Linux Ubuntu operating system. Functionality is verified if a clear, stable video feed is able to be viewed through the HDMI monitor. For initial testing of basic functionality, the guvc-view Linux application was used to record and observe the view-finder of the camera through the operating system.

### 9.2.4 TEST PLAN FOR ZIGBEE USB MODULE

The test plan for the Sonoff Zigbee USB module is to use the Zigbee2MQTT interface to transmit and receive messages between another Zigbee node.

## 10 ADMINISTRATIVE CONTENT

This section covers information about the project budget and the milestones created and accomplished by the group.

### 10.1 PROJECT BUDGET ESTIMATE AND BILL OF MATERIALS

The table below represents a cost estimate for each of the components in this project. These values take into account potential spare parts as well as a safe margin. Our project sponsor has given the team a figure of \$750 to work with as a ballpark estimate for the project. This budget would refer to parts that have to be ordered specifically for this project and costs that come from parts that are readily available at the Florida Space Institute are not factored into this budget. In other words, parts that may be borrowed from the Florida Space Institute, such as the RAMPS 1.4 kit, are included in the bill of materials but are not considered a cost that uses the allotted budget since it is already available for use at the Florida Space Institute lab.

*Table 10.1 Bill of Materials Estimate*

Feature	Quantity	Unit	Price (per unit)	Total
Libre Computer Le Potato Mini	1	# of boards	\$40.00	\$40.00
SONOFF Zigbee 3.0 USB Dongle	1	# of modules	\$31.99	\$31.99
Antenna	2	# of antennas	\$40.00	\$80.00
Arducam IMX708 USB Camera Module 3	1	# of modules	\$49.99	\$49.99
2 Pack, 12V, 6Ah Battery	1	# of packs	\$39.50	\$39.50
PCB Fabrication	3	# of PCBs	\$45.00	\$135.00
NEMA 17 Stepper Motor	8	# of motors	\$13.99	\$111.92
NEMA 23 Stepper Motor	2	# of motors	\$25.99	\$51.98

DRV8825 Stepper Motor Driver Module	3	# of 5 packs	\$11.88	\$35.64
RAMPS 1.4 Kit	1	# of kits	\$33.59	\$33.59
Fuse Kit	1	# of kits	\$7.99	\$7.99
<b>Total Estimated Cost</b>				<b>\$617.60</b>

## 10.2 DISTRIBUTION OF WORK

The table below shows the primary and secondary person responsible for each part of the project.

*Table 10.2 Work Distribution by Component*

<b>Component</b>	<b>Primary Person</b>	<b>Secondary Person</b>
Microcontrollers	Brandon	Eli
Battery	Maria	Nina
Regulator	Maria	Nina
Motor	Nina	Maria
Motor Controller	Nina	Maria
Communications/Antenna	Eli	Brandon
Camera	Brandon	Eli
Charging Station	Maria	Nina
Application Controller	Brandon	Eli

## 10.3 MILESTONES

There are many steps to take for this project to be completed smoothly. Below are two tables that helped the group keep track of timing and milestones. Due to the overlap between Senior Design 1 and 2, the group made an effort to complete both simultaneously. Through the design and prototype, the group can come back and work on the documentation as the project develops. Both tables below show these major milestones as well as important dates. Table \_\_\_\_ is related to the project documentation and Table \_\_\_\_ is related to the prototype development.

*Table 10.3 Project Documentation Milestones*

<b>Project Documentation</b>
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<b>Task</b>	<b>Start Date</b>	<b>Planned End Date</b>	<b>Required End Date</b>
Initial Design Document	08/28/2023	09/08/2023	09/15/2023
60-Page Milestone	08/28/2023	10/27/2023	11/03/2023
Final Report	08/28/2023	11/28/2023	12/05/2023

*Table 10.4 Prototype Development Milestones*

<b>Prototype Development</b>			
<b>Task</b>	<b>Start Date</b>	<b>Planned End Date</b>	<b>Required End Date</b>
Core Component Selection	08/28/2023	10/06/2023	10/06/2023
Individual System Design	09/25/2023	10/20/2023	12/05/2023
Individual System Testing	11/13/2023	11/28/2023	12/05/2023
System Interfacing	11/13/2023	11/28/2023	12/05/2023
PCB Design	10/20/2023	11/28/2023	TBD – SD2
PCB Testing	TBD – SD2	TBD – SD2	TBD – SD2
Prototype Completion	TBD – SD2	TBD – SD2	TBD – SD2

## 11 PROJECT SUMMARY AND CONCLUSION

### APPENDIX A – COPYRIGHT PERMISSIONS

### APPENDIX B - REFERENCES