ELECTRICAL AND COMPUTER ARCHITECTURE

OF AN AUTONOMOUS MARS

SAMPLE RETURN ROVER PROTOTYPE

by

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A THESIS

Submitted in partial fulfillment of the requirements
for the degree of Master of Science
in the Department of Electrical and Computer Engineering
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2016

ABSTRACT

Space truly is the final frontier. As man looks to explore beyond the confines of our planet, we use the lessons learned from traveling to the Moon and orbiting in the International Space Station, and we set our sights upon Mars. For decades, Martian probes consisting of orbiters, landers, and even robotic rovers have been sent to study Mars. Their discoveries have yielded a wealth of new scientific knowledge regarding the Martian environment and the secrets it holds. Armed with this knowledge, NASA and others have begun preparations to send humans to Mars with the ultimate goal of colonization and permanent human habitation. The ultimate success of any long term manned mission to Mars will require in situ resource utilization techniques and technologies to both support their stay and make a return trip to Earth viable. A sample return mission to Mars will play a pivotal role in developing these necessary technologies to ensure such an endeavor to be a successful one.

This thesis describes an electrical and computer architecture for autonomous robotic applications. The architecture is one that is modular, scalable, and adaptable. These traits are achieved by maximizing commonality and reusability within modules that can be added, removed, or reconfigured within the system. This architecture, called the Modular Architecture for Autonomous Robotic Systems (MAARS), was implemented on the University of Alabama's Collection and Extraction Rover for Extraterrestrial Samples (CERES). The CERES rover competed in the 2016 NASA Sample Return Robot Challenge where robots were tasked with autonomously finding, collecting, and returning samples to the landing site.

LIST OF ABBREVIATIONS AND SYMBOLS

3D	Three-dimensional
A	Amps
APXS	Alpha Proton X-ray Spectrometer
ASI/MET	Atmospheric Structure Instrument and Meteorology Package
CERES	Collection and Extraction Rover for Extraterrestrial Samples
CHIMRA	Collection and Handling for Interior Martian Rock Analysis
cm	centimeters
CPU	Central Processing Unit
CheMin	Chemistry and Mineralogy
ChemCam	Laser-Induced Breakdown Spectroscopy for Chemistry and Microimaging
DAN	Dynamic Albedo of Neutrons
DC	Direct Current
eMMC	Embedded MultiMediaCard
E-stop	Emergency-Stop
EEPROM	Electrically Erasable Programmable Read-Only Memory
FTDI	Future Technology Devices International
g	Grams
GHz	Gigahertz
GPU	Graphics Processing Unit
HDMI	High-Definition Multimedia Interface

HazCam	Hazard Avoidance Camera
I^2C	Inter-Integrated Circuit
IBM	International Business Machines
IMP	Imager for Mars Pathfinder
IMU	Inertial Measurement Unit
ISRU	In Situ Resource Utilization
LED	Light-Emitting Diode
LPDDR4	Low Power Double Data Rate Fourth-Generation
LiDAR	Light Detection And Ranging
MAARS	Modular Architecture for Autonomous Robotic Systems
MAHLI	Mars Hand Lens Imager
MARDI	Mars Descent Imager
MB	Megabytes
MEMS	Microelectromechanical system
MER	Mars Exploration Rovers
MHz	Megahertz
MMRTG	Multi-Mission Radioisotope Thermoelectric Generator
MOXIE	Mars Oxygen In Situ Utilization Experiment
MSL	Mars Science Laboratory
MastCam	Mast Camera
N·m	Newton Meter
NASA	National Aeronautics and Space Administration
PADS	Powder Acquisition Drill System

PCB	Printed Circuit Board
PCIe	Peripheral Component Interconnect Express
PID	Proportional-Integral-Derivative
PWM	Pulse Width Modulation
PanCam	Panoramic Camera
RAD	Radiation Assessment Detector
RAM	Random Access Memory
RANSAC	Random Sample Consensus
RCE	Rover Computer Element
REM	Rover Electronics Module
REMS	Rover Environmental Monitoring Station
ROS	Robot Operating System
SAM	Sample Analysis at Mars
SATA	Serial Advanced Technology Attachment
SD-XC	Secure Digital Extended Capacity
SDIO	Secure Digital Input Output
SRRC	Sample Return Robot Challenge
SSR	Solid State Relay
TK1	Tegra K1
TX1	Tegra X1
UHF	Ultra High Frequency
VMEbus	Versa Module Europa Bus
VOR	Very High Frequency Omni Directional Radio Range

USB	Universal Serial Bus
V	Volts
Wh	Watt-hours
°	Degrees

ACKNOWLEDGMENTS

First, I would like to thank everyone involved in the University of Alabama Astrobotics team that helped design, develop, and build CERES; an award winning robot.

1. Joe Kabalin and Josh Yarbrough for their many hours spent with me creating SOLIDWORKS designs and renders;
2. Connor Lawson, Derrill Koelz, Jake Webster, and Richard Belleville for their hard work developing the code;
3. David Sandel for whose thesis on modular software architectures served as a model;
4. Justin Headley for being so bold as to first propose we compete in NASA’s Sample Return Robot Challenge;
5. Dr. Ricks for his extraordinary leadership, guidance, and management of our team.

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CHAPTER 1

INTRODUCTION

The human exploration of Mars has been on the minds of those so willing to dream it for centuries. With Neil Armstrong first setting foot on the Moon in 1969, to the automobile-sized robotic rover, Curiosity, currently traversing the Martian surface, the dream of man stepping foot on Mars has never been so attainable. NASA’s current goal is to put man on Mars by the year 2035 [1]. NASA and others are also investigating the long term goal of creating a human colony on Mars [2] [3]. For a sustainable habitation of Mars, man will have to make use of the natural resources. To date, orbiters, landers, and rovers have all been successfully sent to study Mars and its environment. These missions have provided several scientific discoveries vital to determining what resources will be available. Building from the lessons and discoveries of previous Martian missions, one of the next steps in the evolution of Martian exploration and colonization will be a sample return mission [4]. NASA expects to launch just such a mission in the summer of 2020 [5].

With sheer cost as the primary limiting factor in the exploration of Mars, NASA and other agencies look to reduce the cost of missions. Current estimates to send a payload to Mars is $100,000 per kilogram [6]. Modular platforms would be an avenue for cost reduction. With rovers, whether mission objectives change or on-board technology becomes inoperable, modular platforms can accommodate these changes. Selectively replacing instruments or modular electronic components to change mission objectives or simply to make a repair could provide significant cost reduction over the long term instead of sending an entirely new rover.

1.1 Thesis Statement

This thesis introduces a modular electrical and computer architecture for a robotic platform that meets the following requirements:

1. The architecture will support implementation on a platform comprised of multiple modules than can be added, removed, modified, or reconfigured.
2. The architecture will be scalable, adaptable and flexible by maximizing commonality, modularity, and reusability.

The designed architecture, referred to as the Modular Architecture for Autonomous Robotic Systems (MAARS) was implemented on the University of Alabama's Collection and Extraction Rover for Extraterrestrial Samples (CERES). This robotic platform is a system designed to autonomously find, collect, and return samples for the 2016 NASA Sample Return Robot Challenge (SRRC). CERES features four hardware modules, the Drivetrain module, the Localization module, the Sample Detection module, and the Acquisition module. These modules demonstrate the benefits of modularity, scalability, and adaptability for a robotic rover platform.

1.2 Thesis Outline

This thesis contains six chapters. Chapter 2 begins by providing a summary of relevant background information pertaining to space exploration and human habitation on Mars. Chapter 3 reviews existing Martian rover technologies and implementations and places MAARS in context. Chapter 4 introduces the MAARS architecture and the components that will support a modular and reconfigurable robotic platform. Chapter 5 details an implementation of MAARS on the CERES robotic platform as part of the 2016 SRRC. Finally, Chapter 6 concludes with a summary of the work presented and investigates possible improvements on this design.

CHAPTER 2

BACKGROUND

This chapter covers a brief history of past Martian missions, and a look at future missions helps to provide perspective on where a sample return mission fits in the context of human exploration of Mars.

2.1 In Situ Resource Utilization

Any prolonged human presence on Mars will require humans to make use of Mars' natural resources. Simply relying on supplies from Earth, over 54 million kilometers away, is neither feasible nor practical. In situ resource utilization (ISRU) provides a potential savings of $100,000 per kilogram of cargo launched [6]. ISRU techniques allow for buildings, shelters, launch pads, and other useful structures to be constructed. These structures would be comprised of modular building blocks made of Martian soil [6]. Mining, refining, and processing of both regolith and the atmosphere can yield hydrogen and oxygen which can be used for the production of propellants, pure water for drinking and radiation shielding, and breathable air for life support systems [7]. ISRU will play a pivotal role in space exploration.

2.2 Martian Exploration

To further understand what resources are available, knowledge must be gained about the environment. Numerous scientific expeditions have been launched to Mars; some of those as early as the 1960s. These space probes have included flybys, orbiters, landers, and even rovers that have all visited the planet.

From early flybys from Mariner missions in the 1960s to the landers of the Viking missions in the 1970s, scientists began to piece together information from this previously unexplored planet. Scientific instruments measured the planet's magnetic field, radiation in the atmosphere, and gathered information about cosmic dust [8]. The first pictures returned to Earth depicted a crater-ridden surface and a planet seemingly devoid of life. This new perspective initially reshaped the scientific community's view of life on Mars. Subsequent missions produced higher resolution images that revealed ancient river beds, extinct volcanoes, and large canyons; all evidence of a time when water once flowed on the surface of Mars. These early missions, seemingly bringing about more questions than answers, helped establish a basis for further investigation as the hunt for life on Mars would intensify [9].

In 1997, Sojourner became the first rover to traverse the surface of Mars. Exploring around its lander, Pathfinder, Sojourner analyzed several rocks to determine their chemical composition. This mission would set the stage for more advanced rovers to follow. Spirit, Opportunity, and the Curiosity rover all followed in the coming decades. With each new rover came new discoveries. These rovers became mobile laboratories performing science experiments on the Martian soil and atmosphere. These tests would provide an unprecedented amount of information about the Martian environment, clues to its past, and the resources it contains.

The next step in exploring the surface of Mars is to return a sample back to Earth for further analysis. In 2006, The Mars Exploration Program Analysis Group identified 55 important future science investigations related to the exploration of Mars. In 2008, it was concluded that about half of these investigations could "be addressed to one degree or another" by a Mars sample return mission and that a significant number of the investigations could not be advanced in a meaningful way without analysis of returned samples. The report concluded that a Mars sample return mission would make the most impact on the list of any one single mission [10]. In addition, the Mars Program Planning Group concluded that sample return architectures provide promising intersections of objectives for long term human exploration, science, and technology collaboration [11].

Currently, we have only been able to test samples from Mars, on Mars. All the knowledge gained thus far has been limited by the types of technologies we can send to Mars and by the limited types of testing that can occur. Earth-based analysis allows for more advanced testing and will increase the knowledge of soil properties and prospective life on the planet. Possible health hazards could be identified that would affect human inhabitants. Samples could even be preserved and stored for years and tested again as new testing technologies and techniques arise. Knowledge provided by sample return missions can ultimately broaden what ISRU technologies would be available to inhabitants and ultimately increase the viability of habitation.

The proposed Mars 2020 mission will be the first step of a multistep process to return Martian samples to Earth. This mission will focus on collecting samples of soil and rock and caching them on the surface for collection and potential return by a future mission. Using a coring drill and a rack of sample tubes, approximately 30 samples will be deposited at various locations for a future sample retrieval mission. The Mars 2020 mission expects to launch in the summer of 2020 [5].

CHAPTER 3

RELATED WORKS

For nearly the last two decades, robots have been exploring the surface of Mars. This chapter will place those mission objectives and subsequent designs into context with that of the sample return rover prototype implemented at the University of Alabama.

3.1 Mars Pathfinder and Sojourner Rover

The Pathfinder lander and Sojourner rover reached the surface of Mars on July 4, 1997. The mission carried a series of scientific instruments to analyze the Martian atmosphere, climate, and geology. The mission performed experiments designed to provide information that would improve future planetary rovers. Experiments investigated terrain geometry reconstruction, soil mechanics, path reconstruction by dead reckoning, and vision sensor performance. Additional experiments investigated vehicle performance, thermal conditions on the rover, radio link effectiveness, and material abrasion. In addition to these scientific objectives, the mission served as a proof-of-concept for various technologies such as an airbag landing system and automated obstacle avoidance. Both of these would later be exploited by the Mars Exploration Rovers (MER).

When unfolded, the lander measured 2.75 meters across weighed 370 kilograms, and was covered with 2.8 square meters of solar cells. These solar cells provided up to 1600 watt-hours of power for daytime operation and charged the 50 watt-hour silver zinc batteries for nighttime operation [12] [13]. The Imager for Mars Pathfinder (IMP), a mast-mounted camera, stood approximately 1.5 meters off the ground. The IMP was a stereo camera that was used to image the surface and provide navigation to the rover. Other duties of the IMP included measuring aerosol opacity, characterizing dust particles, investigating magnetic properties, and performing observations about wind velocities. The lander also housed the Atmospheric Structure Instrument and Meteorology Package (ASI/MET). The ASI/MET system acquired atmospheric and acceleration data during the decent of the lander. After landing, the package also included several sensors to measure atmospheric pressure, temperature, and wind [12].

The lander was controlled by a radiation-hardened IBM RAD6000 computer [12]. This computer was capable of 22 million operations per second and had 128 megabytes of dynamic RAM. The RAM was used for the storage of flight software and scientific data. An additional six megabytes of non-volatile memory stored flight software and time critical data [13].

Sojourner had a six-wheeled rocker-bogie suspension. Each aluminum wheel measured 13 centimeters in diameter and could be controlled independently. The rover is 0.65 meters long, 0.48 meters wide, 0.30 meters high when fully deployed [12]. Including instrumentation, the rover weighed 11.5 kilograms [13]. The rover was powered by either a 0.25 square meter solar array or by non-rechargeable lithium-thionyl chloride D-cell-sized batteries. These batteries weighed 1.24 kilograms and provided a limited amount of stored power [12] [13]. Sojourner reached a maximum speed of one centimeter per second and traveled approximately 100 meters in total throughout the lifetime of its operation [12].

Sojourner was equipped with sensors to provide some autonomous navigation capabilities. The rover carried two small black-and-white cameras in the front and a color camera in back. A laser system in conjunction with two forward facing cameras provided capabilities to detect and avoid obstacles [12]. A series of five lasers projected a stripe on the ground out in front of the rover. Cameras then detected the shape of the stripe and used that information to build a contour map of the terrain. When in search of a particular rock, engineers would dispatch (x,y) coordinates to Sojourner. The laser system was used to help successfully identify the desired rock; helping to overcome erroneous odometry data caused by wheel slippage and gyro drift [14]. Communicating back to Earth via the lander, Sojourner’s control system was built around the Intel 80C85 processor. This system had computing speeds of 100,000 instructions per second and featured 500 kilobytes of RAM [13].

The rover (Figure 3.1) was also equipped with a scientific payload, the Alpha Proton X-ray Spectrometer (APXS). The APXS was designed to determine element composition of Martian soil. The APXS was deployed via a single actuator connected to a mechanical linkage. Proper usage dictated that the spectrometer be placed at a variety of heights and rotational orientations. Contact switches mounted to the front of the APXS indicated proper placement and thereby terminated the rover’s motion [15]. Thanks to the mobility of the rover, the APXS was able to analyze several rocks around the lander.

The final data transmission from Pathfinder was received on September 27, 1997. Engineers suspect that depletion of the battery may be to blame for the loss of communication. The battery was only designed to operate for one month. This battery was also responsible for maintaining the rover’s operating temperature, and a drop in temperatures may have ultimately damaged communication equipment. During the 85 days of operation on the surface of Mars, Sojourner sent back 550 images and chemically analyzed more than 15 locations around the lander [12].

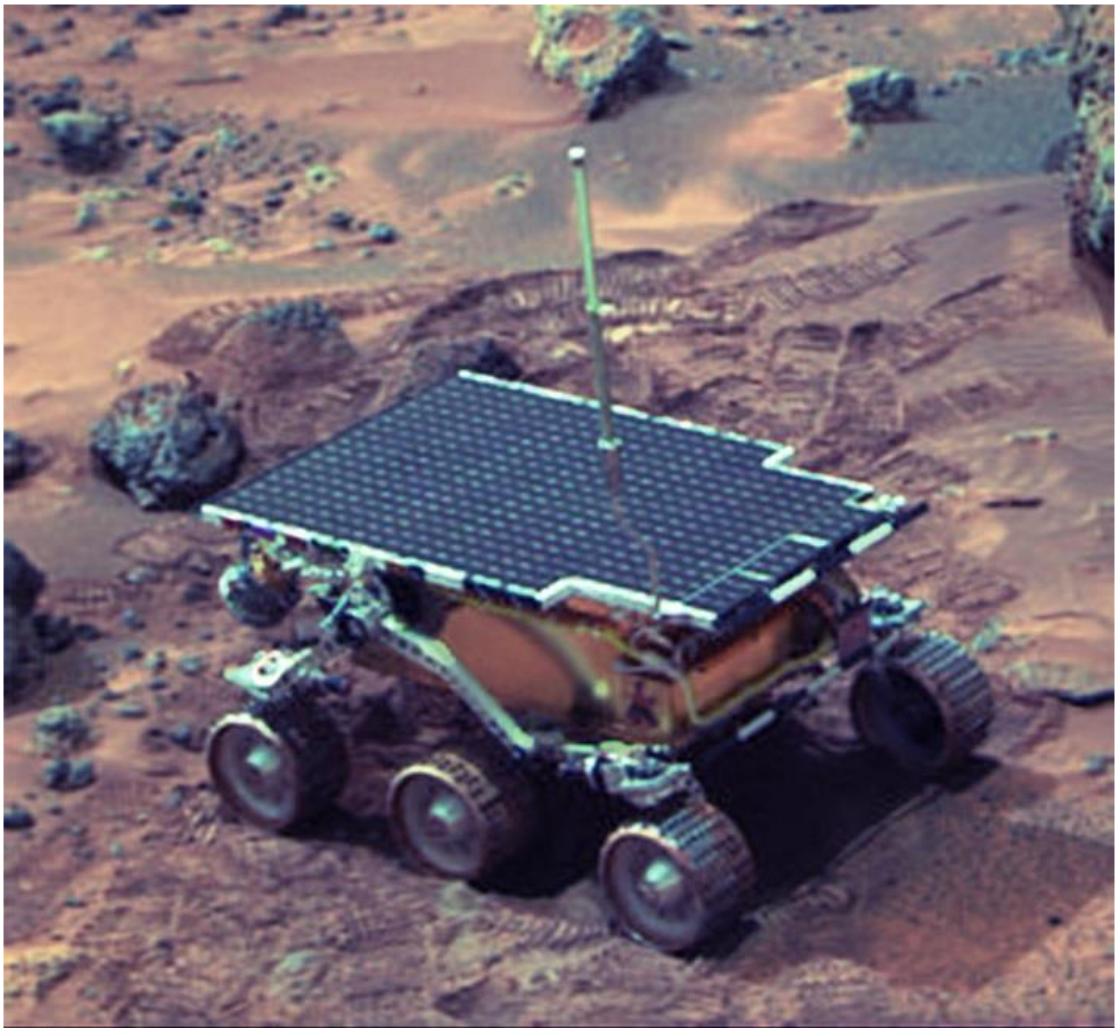

Figure 3.1: Sojourner Rover as Photographed by the Pathfinder Lander [16]

3.2 Mars Exploration Rovers

The Mars Exploration Rovers, designated MER-A Spirit and MER-B Opportunity, landed on the surface of Mars on January 4, 2004 and January 25, 2004, respectively. Their original three month mission sought out to characterize a wide range of rocks and soils that hold clues to past water activity on Mars. Analysis of the Martian environment in this way could help determine if life ever existed on the planet.

Each rover was equipped with a six-wheeled rocker-bogie suspension. Front and rear wheels were equipped with individual steering motors. This not only allowed for an increase in mobility but allowed the rover to grind the 26 centimeter diameter wheels in place and partially submerge the rover in the terrain [17]. This was advantageous during sample collection as it helped prevent the rovers from moving. The rovers had a top speed of five centimeters per second under ideal conditions. Average drive speed was much lower; however, as the hazard avoidance software required a 20 second stop for every 10 seconds of driving to assess the rovers' surroundings. Approximately 100 watts were required to drive each rover. Standing at 1.6 meters long, 2.3 meters wide, and 1.5 meters high, each rover weighed approximately 180 kilograms.

At peak performance, the solar arrays on each rover generated about 140 watts for up to four hours per Martian day. The power system also included two rechargeable lithium ion batteries weighing 7.15 kilograms each. To prevent damage during nighttime temperatures, the electronics were heated by eight radioisotope heater units. These heating units continuously generated one watt of thermal energy [18].

Each rover executed a VxWorks embedded operating system on a radiation-hardened 20 MHz RAD6000 computing platform. This platform featured 128 MB of dynamic RAM, 3 MB of

EEPROM, and 256 MB of flash memory, significantly more than the on-board memory of Sojourner. The computer is housed inside the Rover Electronics Module (REM). MER's computer system used the VMEbus interface to communicate with the various sensors and instruments [19]. The VMEbus architecture incorporated a backplane and allows for modular plug-and-play cards to be easily added and removed from the system. Each rover was equipped with low gain and high gain X band antennas for communication with Earth and a UHF antenna to communicate with orbiting spacecraft.

Spirit and Opportunity both carried a total of nine cameras. The Panoramic Camera (PanCam) consisted of paired black-and-white cameras. The cameras were placed 30 centimeters apart and rendered a 16.8 degree field-of-view both vertically and horizontally. This motorized stereo camera could pivot vertically 90 degrees and spin 360 degrees horizontally. The PanCam was also equipped with an eight position wheel containing color filters. By taking multiple pictures using each of the filters, color images could be reconstructed back on Earth. This greatly reduced the amount of on-board processing required to create and transfer full color images. In addition to the color filters, special solar filters allowed the rovers to use the sun for position and orientation [20]. Two pair of cameras made up the Hazard Avoidance Camera (HazCam) array. Mounted on the front and rear of the rover, these black-and-white cameras had a 120 degree field-of-view and allowed for surface mapping within three meters. The front facing cameras were also used to aid the placement of the robotic arm. The Microscopic Imager was used to take up-close high resolution images of rocks and soil. The last camera pair, mounted to the PanCam Mast Assembly, made up the Navigation Camera (NavCam). The NavCam was elevated to provide a 45 degree field-of-view and was used to look ahead of the rover to aid in route planning. Each of these camera pairings produced 1024 x 1024 pixel, gray scale images at 12 bits per pixel [21].

In addition to an increase in processing capabilities, the MER rovers were outfitted with more on-board scientific instrumentation than their predecessor. An arrangement of five instruments helped perform the various geological field tests. Instrumentation included the PanCam, microscopic imager, miniature thermal emission spectrometer, Mössbauer spectrometer, and alpha particle X-ray spectrometer. A rock abrasion tool augmented the suite of instruments by removing weathered surface material from samples. The spectrometers, microscopic imager, and abrasion tool all shared a turret at the end of the robotic arm [22]. This modular configuration of the arm allowed for multiple instruments to be used without having to provide individual mechanisms to move them.

On January 21, 2004, just weeks after landing, Spirit stopped communicating. As engineers diagnosed the problem over several days, it was determined that poor management of the computer's on-board flash memory led to fault conditions that resulted in more than 60 reboot cycles over a three day period [22]. Engineers solved the problem by uploading new firmware to better manage the flash memory. In May of 2009, Spirit became entrenched in soft soil. Engineers were unsuccessful after several months of attempting to free the rover. NASA ultimately redefined Spirit's mission as a stationary research platform. Operating without the ability to position its solar panels in the sun, Spirit slowly lost the ability to recharge its batteries. Communication with Spirit eventually stopped in March of 2010, and on May 25, 2011 NASA announced it would no longer attempt to contact it. Similar to that of Sojourner, NASA believed many critical components were damaged as a result of cold temperatures [23]. Spirit drove over

7,700 meters and returned more than 128,000 images [24] [25]. The Opportunity rover, seen in Figure 3.2, is still fully operational to this day.

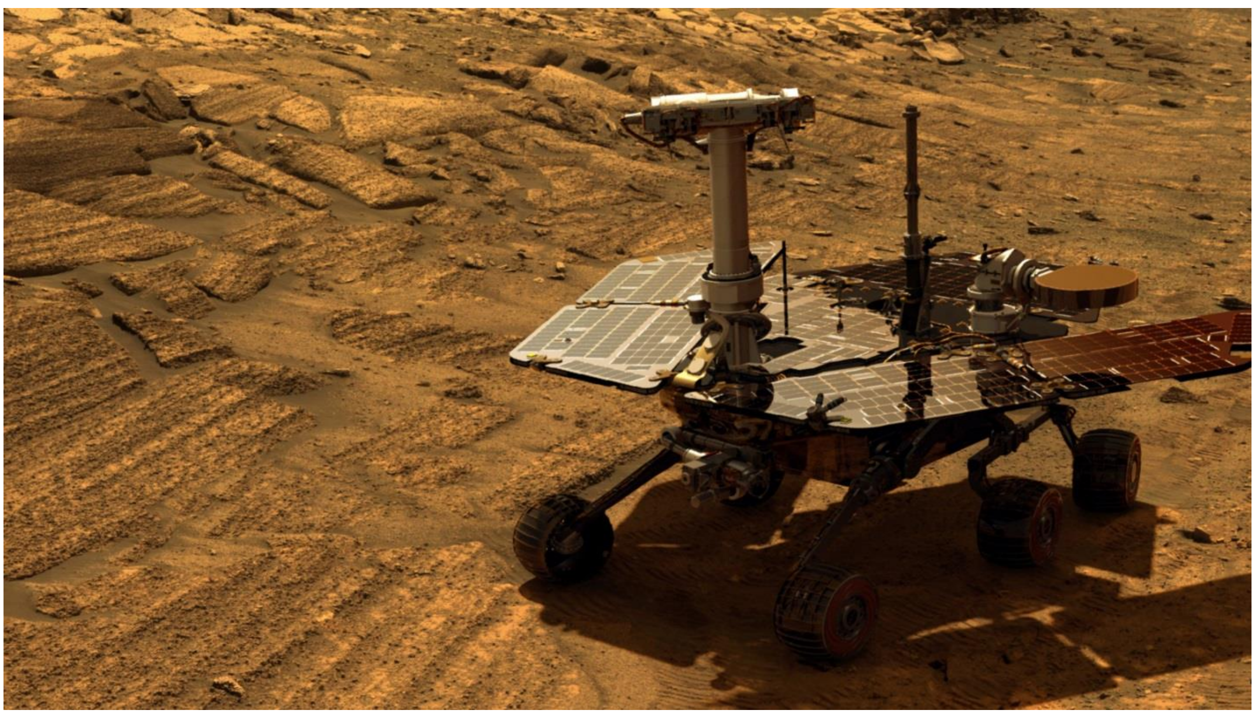

Figure 3.2: Simulated View of Opportunity on the Surface of Mars [26]

3.3 Mars Science Laboratory

The Mars Science Laboratory (MSL) rover, Curiosity, landed on Mars on August 6, 2012. Curiosity's primary mission was planned to last almost two years. Experiments for this mission seek to determine whether life ever existed on Mars and to help prepare for human exploration. Newly implemented landing techniques demonstrated an ability to land large, heavy equipment. This advance in precision landing capabilities paves the way for sending larger equipment needed to support the infrastructure of human explorers [27].

Curiosity features a six-wheeled rocker-bogie suspension with 50 centimeter diameter aluminum wheels. Each corner wheel is independently steerable for increased maneuverability. Specially designed asymmetrical holes in the wheel tread leave behind a pattern in the soil that can be used to verify odometry information. The rover measures 2.9 meters long, 2.7 meters wide, 2.2 meters high and weighs 899 kilograms. Top speed is four centimeters per second [28].

Curiosity receives its power from the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The MMRTG is designed to provide 125 watts of power initially; falling to 100 watts after 14 years. Over the course of a day, the 2.5 kilowatt hours generated results in a 400 percent increase over the MER rovers that were only capable of generating 0.6 kilowatt hours per day [29]. The MMRTG allows for greater mobility as the electrical system is no longer susceptible to changes in sunlight or the changing seasons. Excess heat from the MMRTG is redirected to keep critical components within operating temperatures. This eliminates the need for additional spot heating as seen with previous Martian rovers.

Curiosity is controlled by a pair of redundant on-board computers referred to as the Rover Computer Element (RCE). The RCE features a pair of radiation-hardened 200 MHz RAD750 computing platforms executing the VxWorks embedded operating system. One of the two computers is configured to serve as a backup in the event of a failure with the primary system. With two gigabytes of flash memory, Curiosity has ten times the processing speed and eight times the memory capacity of the MER rovers [29]. Curiosity utilizes both X band and UHF radios to communicate with Earth. X band transmitters and receivers allow for direct communication with Earth but are hampered by speeds of 32 kilobits per second. For faster data transfer speeds, Curiosity uses the UHF radios to communicate to orbiting satellites. Connection speeds with these satellites reach as high as two megabits per second; however, communication with these orbiters are limited to just eight minutes a day [30] [31].

With an increase in processing power, comes an increase in capabilities. Curiosity utilizes a total of seventeen cameras. The Mars Descent Imager (MARDI) was used to capture video as the rover landed. On the end of the robotic arm is the Mars Hand Lens Imager (MAHLI). MAHLI is capable of taking high resolution, close-up, color photos and allows geologists back on Earth to view features of the Martian rock and soil that are smaller than the diameter of a human hair. A total of eight HazCams are present; two pair each on the front and rear of the rover. The Laser-Induced Breakdown Spectroscopy for Chemistry and Microimaging (ChemCam) is used to fire a laser at rocks and soil and analyze the composition of the vaporized material. Similar to the MER rovers, Curiosity features two duplicate Mast Camera (MastCam) systems. These cameras produce color images and videos as well and three dimensional stereo images. Four black-and-white NavCams are mounted to the mast as well [29].

In addition to the ChemCam and MAHLI, Curiosity contains a suite of scientific instruments. Mounted to the mast below the ChemCam and MastCam is the Rover Environmental Monitoring Station (REMS). The REMS essentially serves as a Martian weather station by monitoring many environmental factors like air and ground temperature, humidity, wind velocity, atmospheric pressure, and ultra violet radiation. Mounted in the rear of the rover is the Radiation Assessment Detector (RAD). The RAD is one of the first instruments designed specifically for the preparation of human explorers as it is responsible for measuring and identifying high-energy radiation on the surface of Mars. Curiosity also carries an APXS similar to that one used on the previous two missions. In an effort to identify both water and various minerals in the soil, Curiosity utilizes the Dynamic Albedo of Neutrons (DAN) and the Chemistry and Mineralogy (CheMin) instrument, respectively. Finally, Curiosity carries the Sample Analysis at Mars (SAM) instrument suite. Taking up nearly half of the scientific payload on-board, the SAM suite features a mass spectrometer, gas chromatograph, and laser spectrometer. Soil samples collected from the robotic arm are deposited in the SAM for analysis [32].

Curiosity uses a robotic arm to carry out many of the scientific experiments. The robotic arm offers five degrees-of-freedom and carries five devices mounted on a turret. The turret holds the APXS, the MAHLI, the Powder Acquisition Drill System (PADS), the Dust Removal Tool (DRT), and the Collection and Handling for Interior Martian Rock Analysis (CHIMRA). The primary workspace for the arm is limited to the volume of an upright cylinder that measures 80 centimeters in diameter and is 100 centimeters high [33].

In February of 2013, NASA engineers were forced to address yet another memory glitch with a Martian rover. Curiosity’s backup computer was used to take over full operation as engineers worked on a solution for the primary computer. During the initial troubleshooting phase for the primary, the secondary computer also encountered a software problem and put itself into safe-mode. The safe-mode status was triggered when a command file failed a size check. Engineers ultimately decided to delete this file as it was no longer needed. This solution returned both processors to full functionality [34] [35]. The redundant CPU architecture ensures an important layer of protection that allows Curiosity to continue to operate when it may be inoperable otherwise.

Engineers at NASA are also keeping a close eye on the degradation of Curiosity's drive wheels. Traveling from the landing site to Mount Sharp, Curiosity encountered terrain littered with sharp rocks. Images returned from the MAHLI camera have revealed several large punctures. Longevity testing with identical wheels on Earth has indicated that the wheels should hold up long enough to reach the mission's remaining destinations [36]. To date, Curiosity has driven just over 14 kilometers during its four years of operation [37]. Pictures of Curiosity on Mars as well as next to both a MER rover and Sojourner can be seen in Figure 3.3 and Figure 3.4.

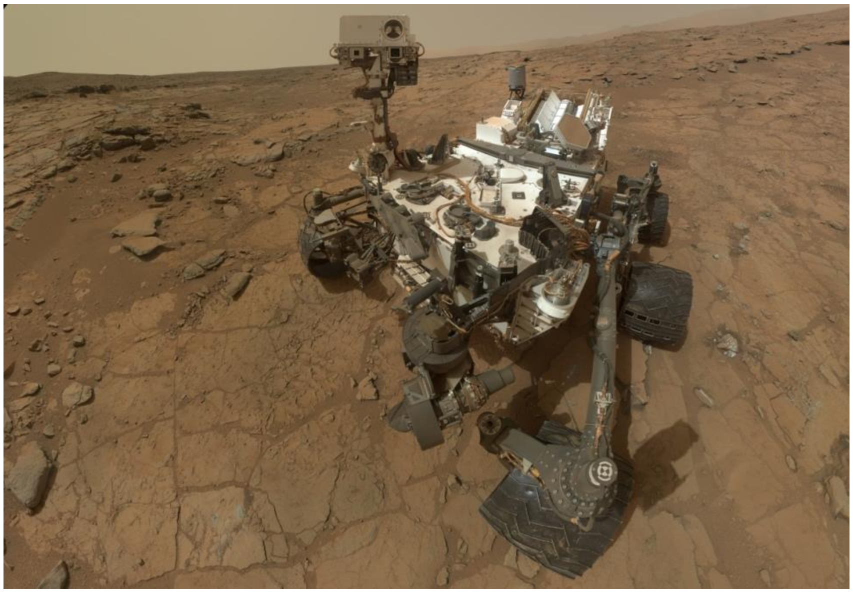

Figure 3.3: Curiosity Rover's Self Portrait at the John Klein Drilling Site [38]

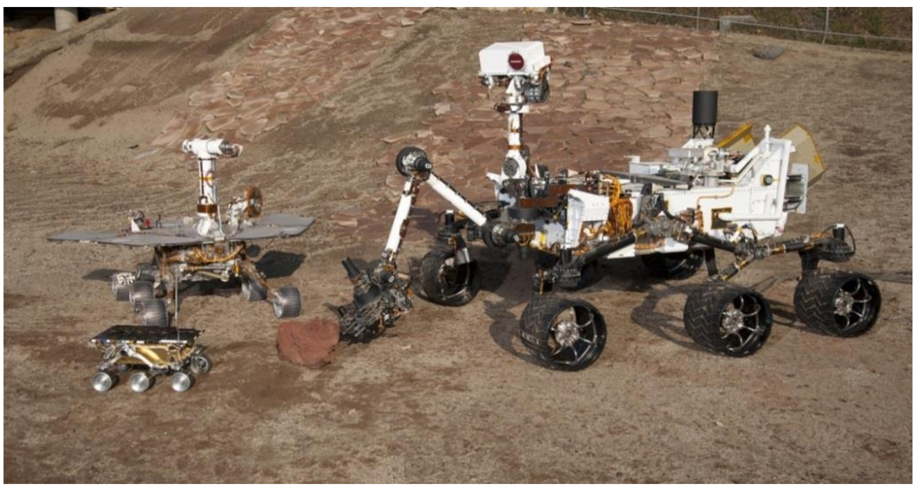

Figure 3.4: Curiosity next to past Martian Rovers [39]

3.4 Mars Sample Return

Plans are currently in the works for a Mars sample return mission. NASA's Mars 2020 mission will set out to further probe the Martian environment in the hunt for evidence of past microbial life and to assess its past habitability [5] [40]. Unlike any mission before it, the Mars 2020 rover will have the ability to collect and store samples. Core samples from rocks and soil will be stored in sample tubes and placed at strategic locations to be retrieved by a future mission. Scientific instruments on the rover's robotic arm will be able to initially analyze samples to better determine from where to collect samples [5].

The Mars 2020 rover will be based on the MSL's Curiosity configuration. Seven scientific instruments, seen in Figure 3.5, have been selected. One of these instruments, Mars Oxygen In Situ Utilization Experiment (MOXIE), will attempt to produce oxygen from the native atmosphere. If successful, systems similar to MOXIE could be utilized on a larger scale to provide life-sustaining oxygen for human habitation or to provide liquid oxygen to fuel the rocket of a return trip to Earth [41].

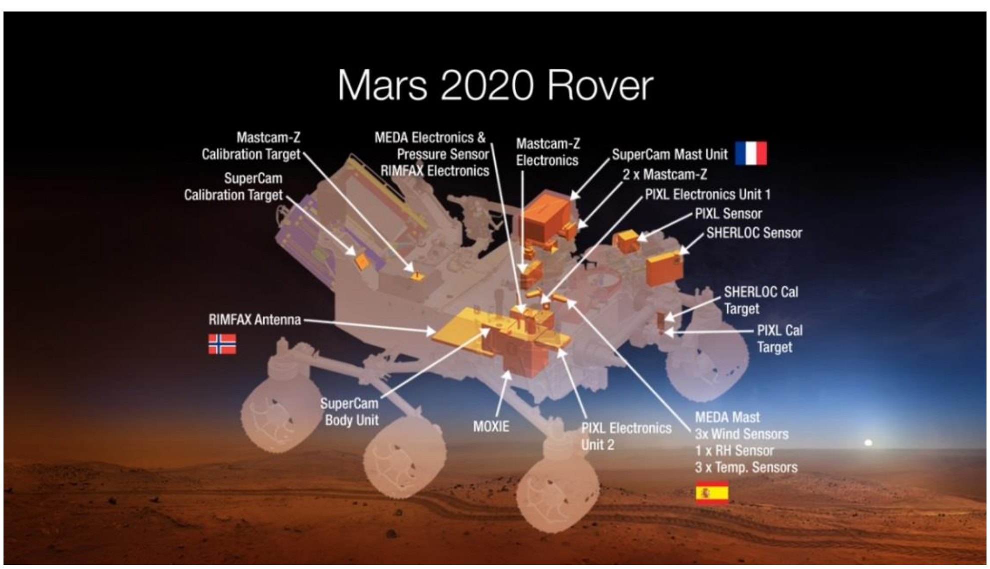

Figure 3.5: Proposed Instrumentation for Mars 2020 Mission [41]

3.5 Future Rover Trends

As NASA continues to expand its exploration of Mars, the rovers used for these tasks are becoming more sophisticated. More advanced sensors and scientific payloads are being employed for more ambitious missions. This trend is shown with the past Mars rovers and is expected to continue. What was low resolution camera images from Sojourner became high resolution on later rovers. What was one pair of cameras forming a single stereo camera sensor on Pathfinder became eight camera pairs on Curiosity. Where Sojourner relied on Pathfinder for path planning and navigation, the later rovers included on-board electronics for all their navigational needs. Where Sojourner traveled to locations immediately adjacent to the Pathfinder lander and was designed to operate on the Mars surface for only one month, Curiosity has traveled over 14 kilometers during its more than four years on the planet.

With these expanded mission objectives and improved on-board technologies, NASA engineers must continue to improve power and processing capabilities. Each iteration of rover discussed previously has significantly more computing resources than its predecessors, including both processing speed and memory. Improved processing and memory are needed as the size and number of images increase (Sojourner took 550 images during its mission, while Spirit took 128,000 images) and more advanced navigational algorithms are performed on-board. As more advanced sensors generate even more data, these improvements will continue to be necessary for future rover designs. Similarly, power generation demands will continue to increase to support the addition of more sensors and science payloads, as well as longer mission durations.

To address these future needs, NASA engineers are investigating rover architectures that emphasize commonality as opposed to customization. This new emphasis would support modular development of capabilities that could then be shared across mission platforms.

Modularity offers several advantages including scalability, serviceability/maintainability, reusability, redundancy, and simplification of the design process. For example, an autonomous navigation module could be developed that could be used on multiple rovers. Each rover would simply have to provide the interfaces necessary to use the module. Similarly, standard sensor packages and power generation systems could be developed as individual modules. Power modules could even be combined to generate the necessary power for any specific mission. Rover design would be simplified with this approach as each rover would become some combination of standard modules as opposed to a completely customized platform. As technologies improve, modularity also supports scalability to address future needs for more power, more processing speed, and more memory. This approach also improves serviceability/maintainability as modules from one rover can be moved to another rover if necessary or simply removed and replaced. While this modular approach offers a less optimized design for any one specific mission, the overall benefits it provides to multiple missions are significant. This conclusion is demonstrated by the following quote from NASA:

> "By investing in state-of-the-art technologies, NASA is focusing on developing resilient architecture concepts specializing in critical capabilities across a range of missions. To achieve this, NASA is focusing on maximizing flexibility and adaptability through commonality, modularity, and reusability" [42].

3.6 CERES

CERES is a rover developed at the University of Alabama to perform a Martian sample collecting mission. The goal of the project was to create a rover based upon a modular architecture to provide scalability and the other design benefits mentioned by NASA engineers. CERES is not built using space-rated hardware and does not make use of power generation hardware like solar cells for charging batteries. Instead, CERES is designed for simulated Mars missions carried out on Earth, and it makes use of more cost-effective hardware to demonstrate the benefits of its design.

The mission for which CERES is designed assumes a lander has delivered the CERES rover to the surface of Mars. From the landing site, CERES is tasked with searching the Martian surface for specific geological samples, collecting those specific samples, storing the samples for transit in such a way as to prevent contamination between samples (the samples cannot touch each other), and returning the samples on-board the rover to the landing platform. All electronics and processing are done on-board the rover. However, the lander does have a static, non-powered fiducial to aid with localization and navigation.

While modularity and redundancy are concepts that NASA has already used in orevious rovers, there seems to be no formal architecture approach to rover design based upon these ideas. For example, the VMEbus is a modular architecture used on the MER rovers and on Curiosity, with Curiosity featuring redundant computing systems. However, each successive rover design fails to build upon a common architecture that supports both power and computing. MAARS is an attempt to formalize a modular rover architecture that can serve as a common design upon which a series of rovers can be built, each benefiting from all the advantages of such a design.

CHAPTER 4

MODULAR ARCHITECTURE FOR AUTONOMOUS ROBOTIC SYSTEMS

4.1 The MAARS Architecture

The CERES rover is the first implementation of a modular architecture known as the Modular Architecture for Autonomous Robotic Systems (MAARS). Developed at the University of Alabama, MAARS is an attempt to formalize several concepts from early Martian rovers providing modularity and reconfigurability. MAARS decomposes the mission objective into tasks which are then carried out by specific actions performed by specific hardware. By grouping related tasks, actions, and hardware into units, modules are created as shown in Figure 4.1.

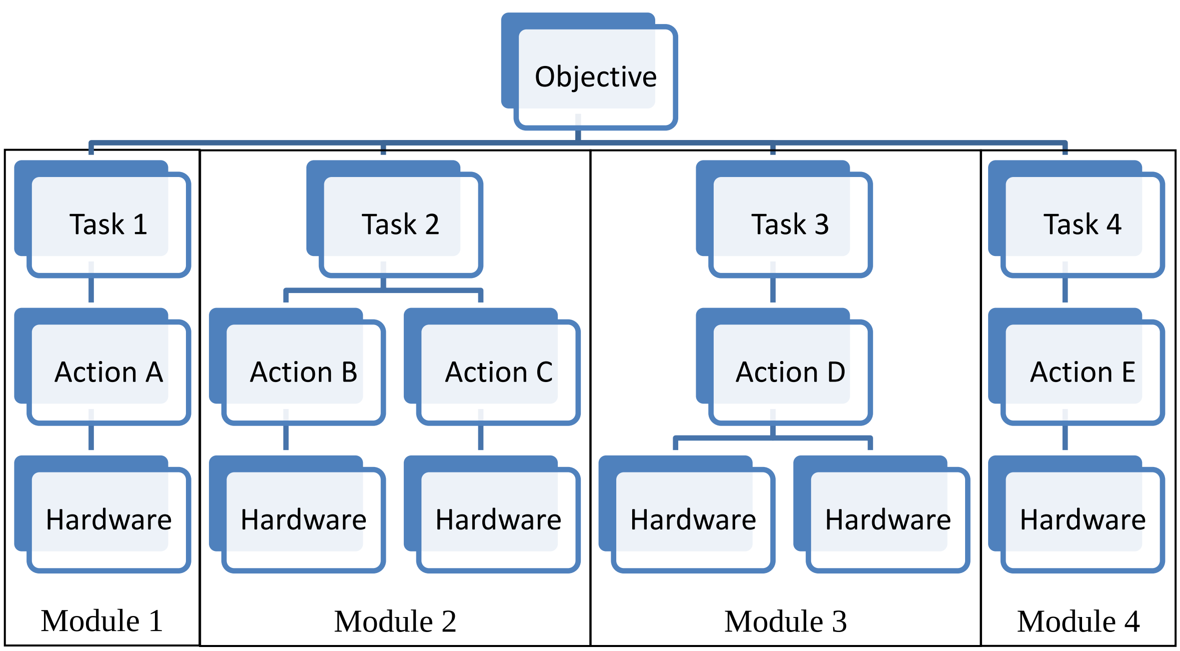

Figure 4.1: System Objective Decomposition and Modularization

Here, each module contains its own power supply, computing platform, sensors, and supporting hardware in order to complete its dedicated task. Each module is functionally independent of every other module within the system. However, modules are interconnected via a common communication interface, shown in Figure 4.2, to allow for cooperative task completion to achieve the singular objective the robot was designed to accomplish. The intercommunication capabilities among the modules are critical to the success of MAARS by providing reconfigurability across modules when necessary.

This loose hardware architecture provides engineers with much freedom when selecting intra-module and inter-module computing and networking hardware. Each module's computing platform can be a single or multiprocessor and can even be arranged as a distributed computing platform itself. The interconnection network can also take many forms from basic serial connections to more advanced, higher speed networks and switches, and further supports inter-module distributed computing. Computing platforms can be the same or different from module to module leading to support for either homogeneous or heterogeneous system-wide computing systems. Similarly, the general nature of the architecture supports various software interfaces within and among the modules from shared memory to message passing. As a result, no specific operating system or software interface is required. A distributed software system can be used across all the modules, or each module can execute its own dedicated software. As modules are added or replaced, existing hardware and software interfaces must be maintained.

4.2 MAARS Benefits

Using this form of system decomposition, the MAARS architecture is independent of the mission and the specific hardware used. With each module being functionally independent from the other modules, MAARS becomes a highly scalable architecture. Modules may be easily added to, removed from, or reconfigured in the system without impacting the functionality of any other module. This independence also leads to flexibility and adaptability at both the module and system levels. At the module level, changes in the requirements for the actions to be performed can be limited to the scope of the module. Sensors and supporting hardware can be added or removed without negatively impacting the functionality of other modules. At the system level, additions of new tasks are easily addressed with the addition of a new module. The distributed power supply removes a single point of failure at the system level allowing functioning modules to continue to operate despite a power failure on another module.

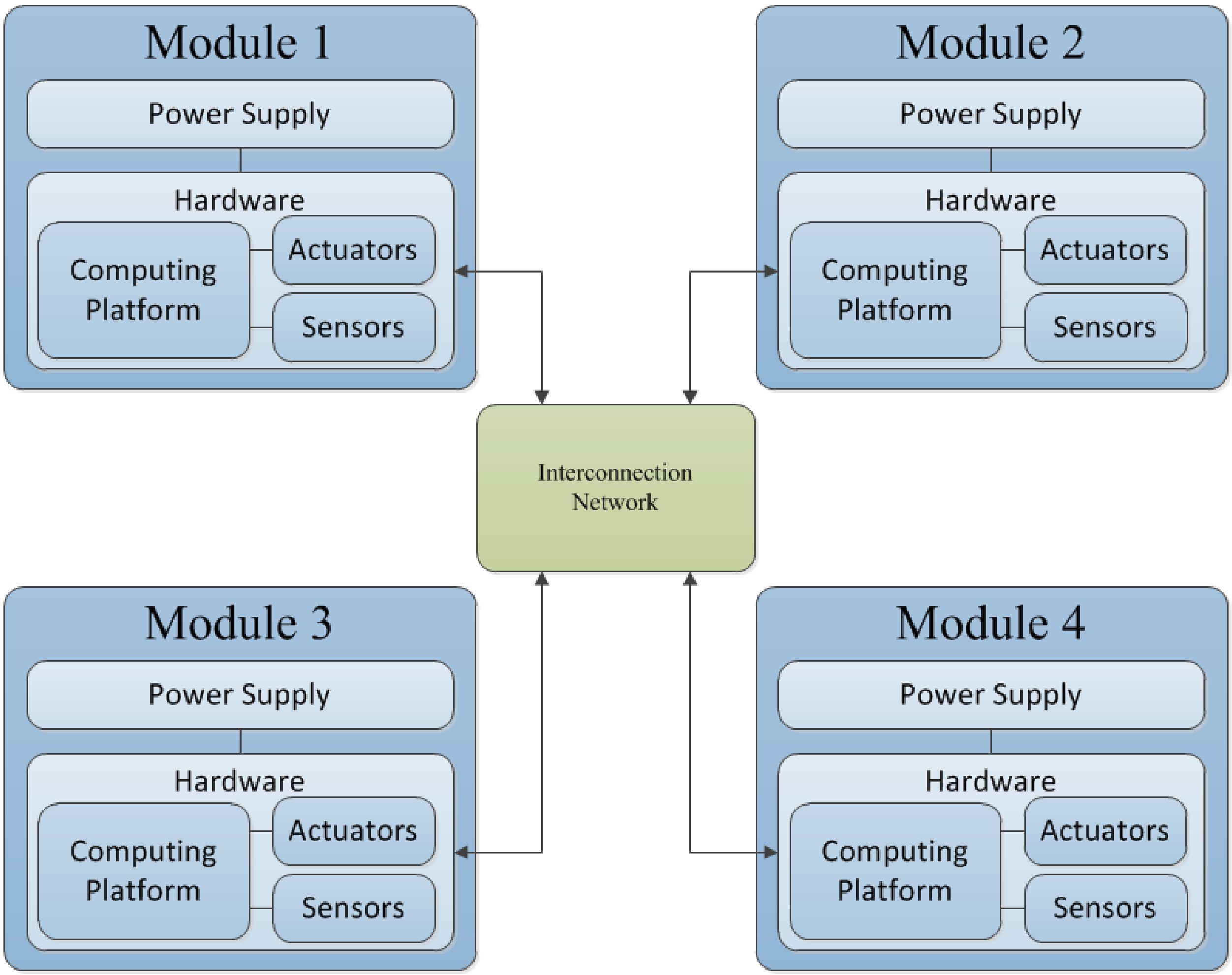

Figure 4.2: Module Composition and Intercommunication

CHAPTER 5

COLLECTION AND EXTRACTION ROVER FOR EXTRATERRESTRIAL SAMPLES

To demonstrate the benefits of MAARS, the design was implemented on the CERES platform to address the 2016 SRRC. This chapter describes the objectives of the challenge, how MAARS was implemented on the robot, and its benefits.

5.1 NASA Sample Return Robot Challenge

The 2016 NASA Sample Return Robot Challenge is a competition that sets out to "develop new technologies or apply existing technologies in unique ways to create robots that can autonomously seek out samples and return to a designated point in a set time period". Robots are "required to navigate over unknown terrain, around obstacles, and in varied lighting conditions to identify, retrieve, and return these samples" [43].

Robots have two hours in which they must retrieve a variety of samples and deliver them back to a starting platform. This starting platform is used to represent the landing sight of a robot during a Martian mission. Custom navigational beacons can be attached to the starting platform to assist the robot. The drive speed of the robot is limited to two meters per second. Several technologies that would not transfer well to an actual Martian mission are prohibited. These prohibited technologies include:

1. Sensors containing instrumentation that rely on the earth's magnetic field;
2. Earth-based radio technologies such as GPS, VHF Omni Directional Radio Range (VOR), or cell phone networks;
3. Ultrasonic and other sound based sensors.

Finally, robots are required to allocate space to carry a special payload, presented by event officials, which may contain a strong magnetic force, frequency jammer, and/or a WiFi encryption device to disable usage of any prohibited signals or technologies. All robot operation must be completely autonomous without any human input or interaction.

5.1.1 Competition Arena

The competition arena is hosted on the site of a large outdoor park, Institute Park, adjacent to the campus of Worchester Polytechnic Institute in Worchester, Massachusetts. The arena is approximately 80,000 square meters, features a rolling terrain, and contains several obstacles including trees, rocks, a small pond, and a covered pavilion area. A satellite image and limited topographical data are provided. Orange construction fencing forms the perimeter of the arena and the competition is hosted only during daylight hours. Topographic information and areas of interest can be seen Figure 5.1.

Figure 5.1: Competition Arena Satellite (above) and Topographical (below) Maps with Areas of Interest [44]

5.1.2 Starting Platform and Home Beacon

Before a competition attempt begins, robots are oriented on a starting platform (Figure 5.2) and placed in a starting location within the competition arena. The starting platform is made of wood and measures 2 meters x 2 meters. Fifteen degree ramps are placed on the front and sides of the platform to allow for a smoother egress of the 15 centimeter high platform onto the ground.

Home beacons are permitted to assist the robot in localizing and navigating back to the starting platform. This navigational beacon is used to further represent the lander and would be available for a robot to use during a Martian mission. Secured to an additional platform at the rear of the starting platform, beacons may not weigh more than 15 kilograms and be contained within height, width, and depth restrictions of 2 meters x 2 meters x 0.43 meters.

Figure 5.2: Starting Platform and Home Beacon

5.1.3 Samples

The competition categorizes the samples based on their level of difficulty to acquire. Sample characteristics for each category are described in Table 5.1. The first sample category is the pre-cached sample. This sample "represents a sample that has already been contained by a rover on the planet prior to your arrival and is awaiting collection" [43]. Easy and intermediate samples consist of various colored rocks while hard samples contain unique, engraved, identifying marks (Figure 5.5). Examples and possible colors of samples can be seen in Figure 5.3 and Figure 5.4, respectively. All competition samples will range in size between 1 and 20 centimeters and will have a mass between 100 and 1000 grams. A maximum of 25 points can be scored if all samples are properly collected.

Table 5.1: Sample Characteristics [43]

Category	**Quantity**	**Point Value**	**Characteristics**
Pre-cached	1	1	A cylinder slightly under 8cm in diameter, 8cm in length, and has a standard hook interface
Easy	3	1	Rock, painted purple, with a major axis of 10-12cm and a mass of 700-1000g
Intermediate	3	2	Rock, painted within the HSV range of 240-60, with a major axis 6-8cm
Hard	3	5	Non-ferrous metal object engraved with a unique, rectilinear, identifying mark

Figure 5.3: Pre-cached (left) and Easy (right) Sample

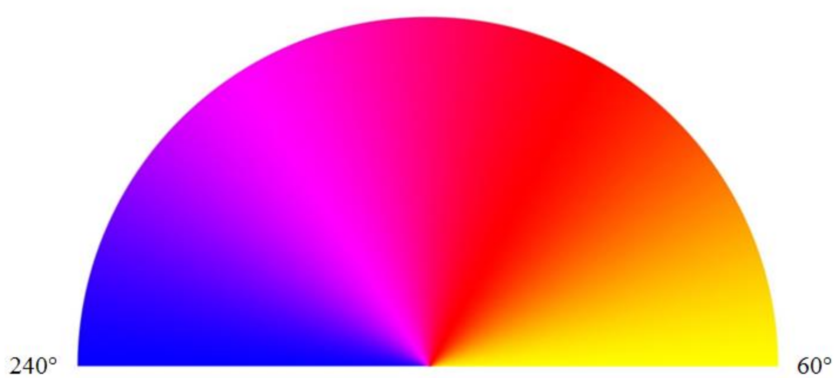

Figure 5.4: Intermediate Sample Color Range [45]

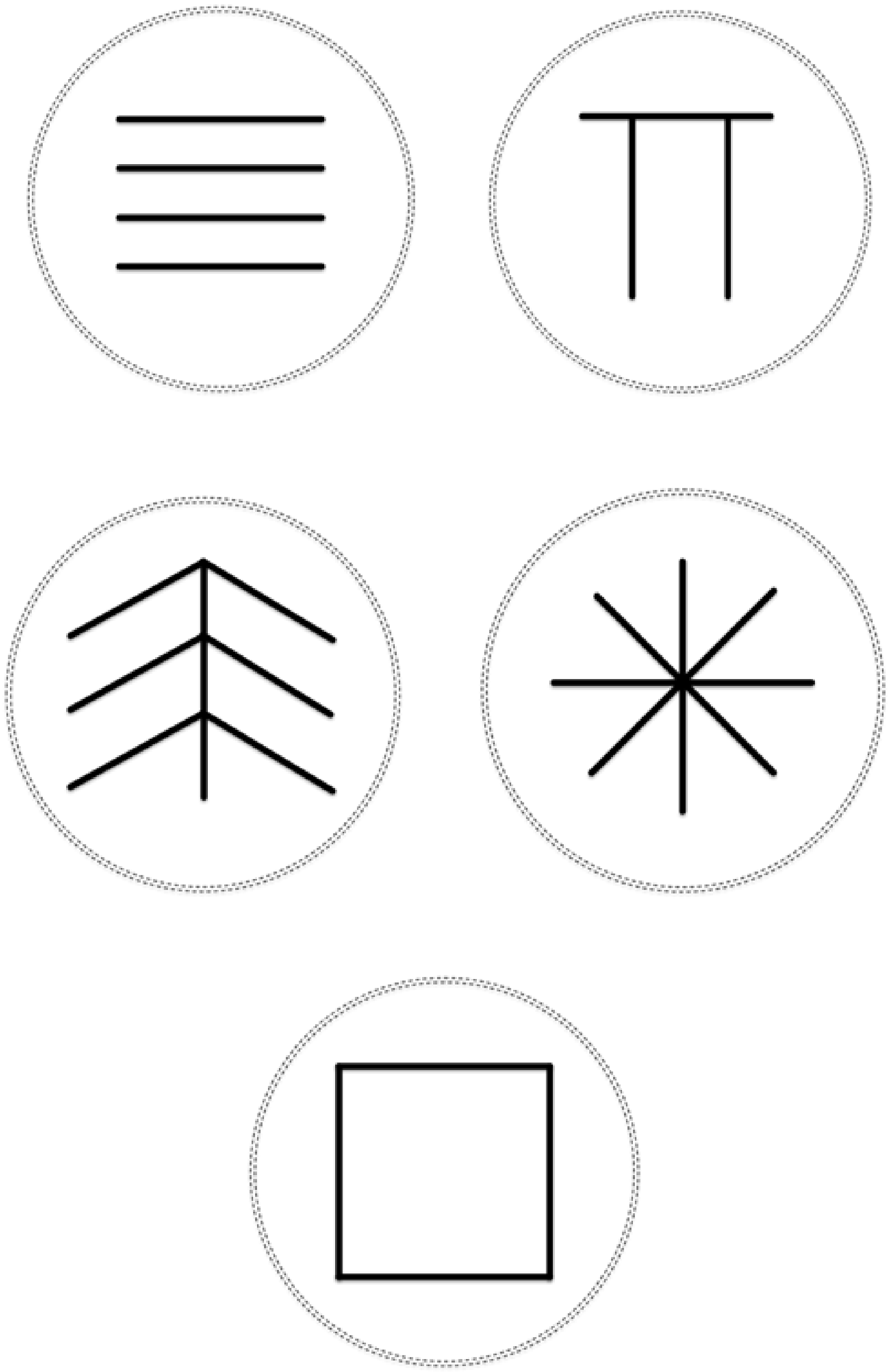

Figure 5.5: Identifying Marks for Hard Samples [46]

5.2 CERES Platform

Alabama Astrobotics, from The University of Alabama, designed, built, and tested an autonomous, robotic, sample collection rover named CERES for entry into the 2016 NASA SRRC. The CERES platform uses the MAARS architecture and serves as a case study for its evaluation.

To qualify for competition, CERES must meet several physical requirements. Robots must be no larger than 1.5 meters x 1.5 meters x 1.5 meters in its starting configuration and may not exceed a mass of 80 kilograms [43]. CERES overall dimensions are 1.2 meters long, 1.05 meters wide, and 0.74 meters high. CERES has a total mass of 57 kilograms. A payload shelf, emergency stop button, and safety light are also mounted in the rear. CERES' competition configuration can be seen in Figure 5.6. Though not optimized, the modular design added approximately five kilograms to the rover's mass and did not adversely affect its ability to fit within the starting dimensions.

CERES is equipped with a six-wheel, triple rocker drivetrain. The drivetrain has two independent twin rockers mounted toward the front of the frame, one on the right and one on the left. A third independent rocker is mounted at the rear of the chassis and serves as the third leg in a tripod configuration. This triple rocker design helps to keep the wheels on the ground while traversing uneven terrain and requires no mechanical interface between individual rockers.

The wheels are made from solid core polyurethane rubber. To help CERES avoid obstacles, the chassis features a 10 centimeter ground clearance and each drive motor and accompanying gearbox are partially recessed into the wheel.

Mounted to the top of the chassis is the electronics enclosure. The electronics closure houses the individual electronics shelves for each module. The dimensions of the electronics enclosure are 0.62 meters long x 0.61 meters wide x 0.15 meters high. Access to the electrical components is achieved through the use of five detachable acrylic doors that are located on the front, left, and right sides of CERES. Electronics are mounted to sliding acrylic shelves located within the electronics enclosure. The sliding shelves allow for easier serviceability.

Figure 5.6: CERES Platform

5.3 Architecture Implementation

The mission objective was decomposed into four tasks leading to an architecture with four modules. These four modules consist of the Drivetrain module, the Localization module, the Sample Detection module, and the Acquisition module. Shown in Figure 5.7, these modules allow CERES to accomplish all necessary tasks to complete the challenge. The Drivetrain module provides locomotion, obstacle detection, communication among modules and with a remote control station, as well as safety. The Localization module determines the robot's location and pose within the arena. The Sample Detection module includes all the components

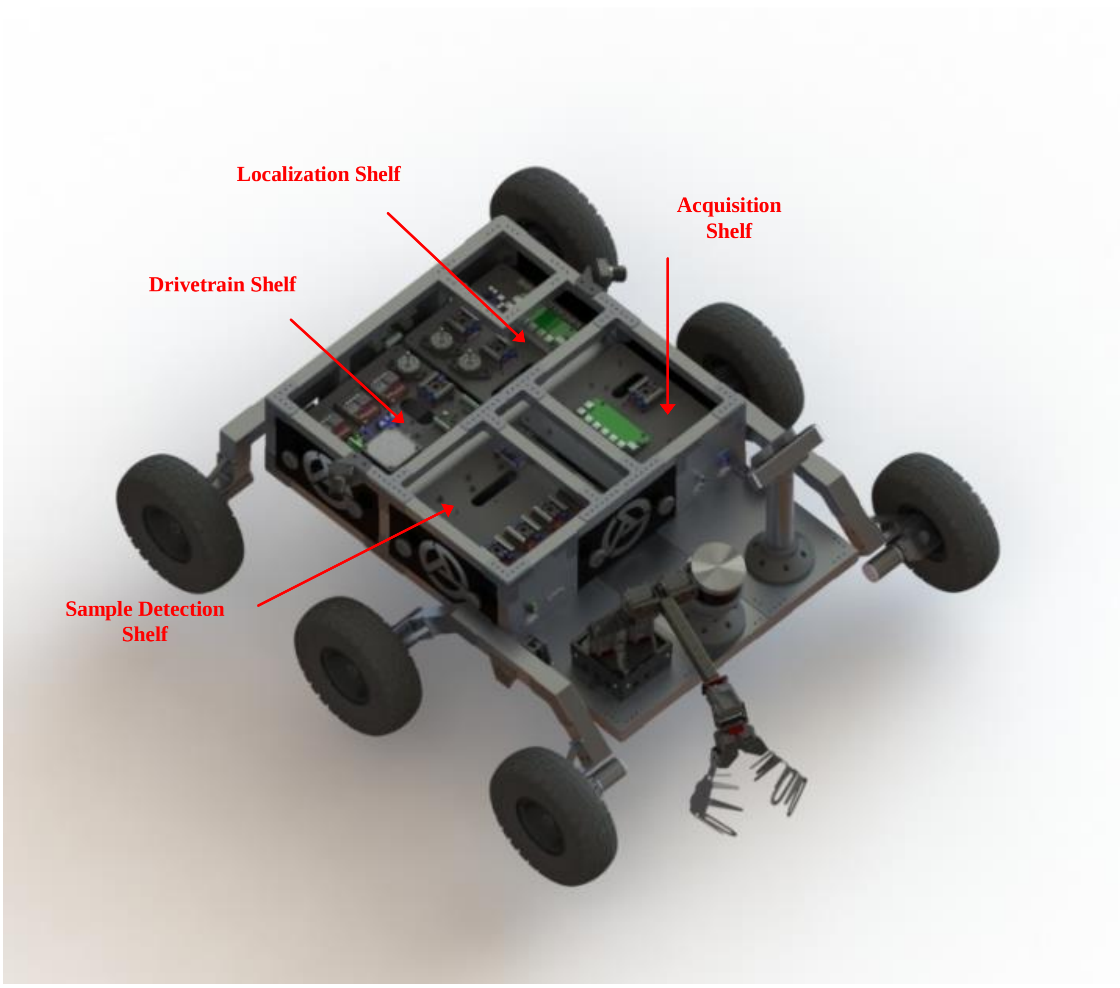

Figure 5.7: CERES Module Locations

needed to search for and detect samples. Finally, the Acquisition module includes all the components needed to specifically locate a sample and load it on-board. Design constraints were placed on the modules to maximize the amount of common hardware used throughout the system. Shown in Figure 5.8, each module, communicates via Ethernet through a central network switch.

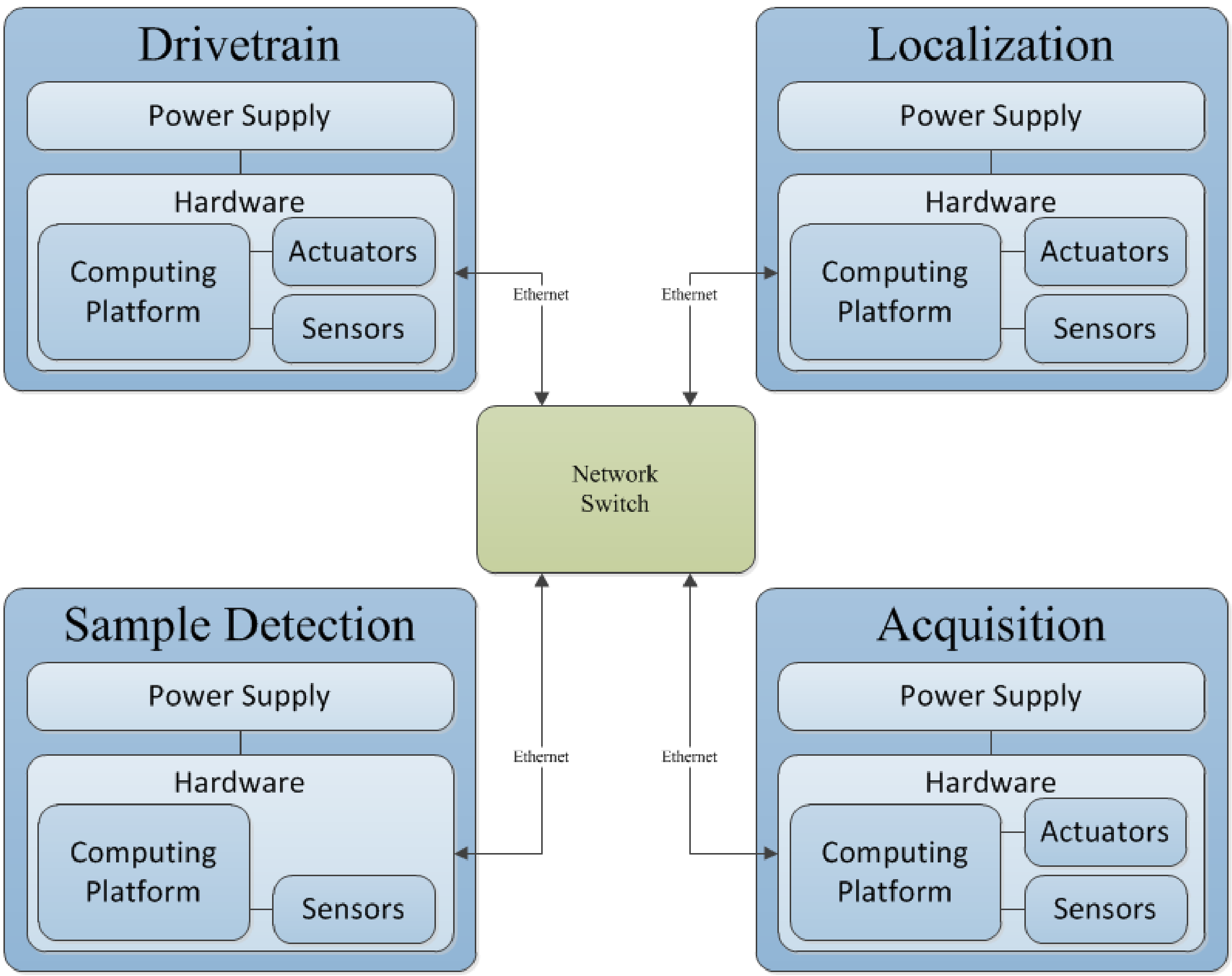

Figure 5.8: CERES Module Composition and Intercommunication

5.3.1 Common Components

One of the primary benefits of MAARS is hardware reuse. This manifests itself in the form of common hardware components used across all modules. This common hardware for CERES includes various power distribution components as well as computing platforms.

5.3.1.1 Power Distribution

All of CERES four modules feature identical interfaces for providing power to the various electronics and sensors. CERES carries a total of six batteries during a two hour competition run. Each E-Flite battery (Figure 5.9) contains five lithium polymer cells and is rated at 18.5 volts and has a five amp hour capacity [47]. The Drivetrain module uses three batteries while each of the other three modules requires only one. In the event of changes to hardware or mission objectives, each module's power system provides support for expansion of additional batteries. SB120 connectors [48] allow batteries to be easily swapped in and out during operation. Battery requirements for each module are shown in Table 5.2.

By using the same type of battery across all modules, this implementation draws on the MAARS philosophy of maximizing commonality. However, each module retains the freedom to customize size, capacity, and technology requirements that best fit the constraints of the particular module. Preserving the ability for future optimization increases the system's reusability. Singular, centralized power systems that utilize lithium polymer batteries require that battery voltages across each battery be synchronized prior to use. In this distributive power configuration, that concern is limited to the scope of a module and allows for more flexibility between the modules.

The distributed power system also increases system reliability and adaptability. In the event of a power failure, the loss in system capability is only limited to the task performed by that particular module. This provides the robot the chance to continue on with its mission albeit with reduced capability. In the event of expansion, power requirements for existing modules remain unchanged and need not factor into consideration of the new module and its power requirements, providing enhanced options.

As one can see in Table 5.2, the three batteries specified for the Drivetrain module provide only 75.6% of the power required for two hours of continuous driving operation. The modularity and expandability of the architecture proved helpful here as two additional batteries were easily added to the drivetrain module on the site of the competition without impacting any other part of the system.

Figure 5.9: Battery and Accompanying Power Connector

Table 5.2: Power Requirements

Module	Number of Batteries	Allocation	Watt-hour Usage
Drivetrain	3	277.5 Wh	210 Wh
Localization	1	92.5 Wh	18 Wh
Sample Detection	1	92.5 Wh	10 Wh
Acquisition	1	92.5 Wh	24 Wh

Before power can be applied to downstream hardware, it must first pass through a power relay and high amperage distribution posts. Each module on CERES incorporates a Tyco Kilovac Relay [49] (Figure 5.10). This relay has a coil voltage of 9-36 volts and supports a continuous current of up to 500 amps. Each of these four relays are connected to an emergency stop button (E-stop) that allows for all of the batteries to be electrically isolated from any electronics at the push of the E-Stop button. The power distribution layout for all four modules can be seen in Figure 5.11.

Figure 5.10: Distribution Post (left) and Tyco EV200AAANA Relay (right) [49]

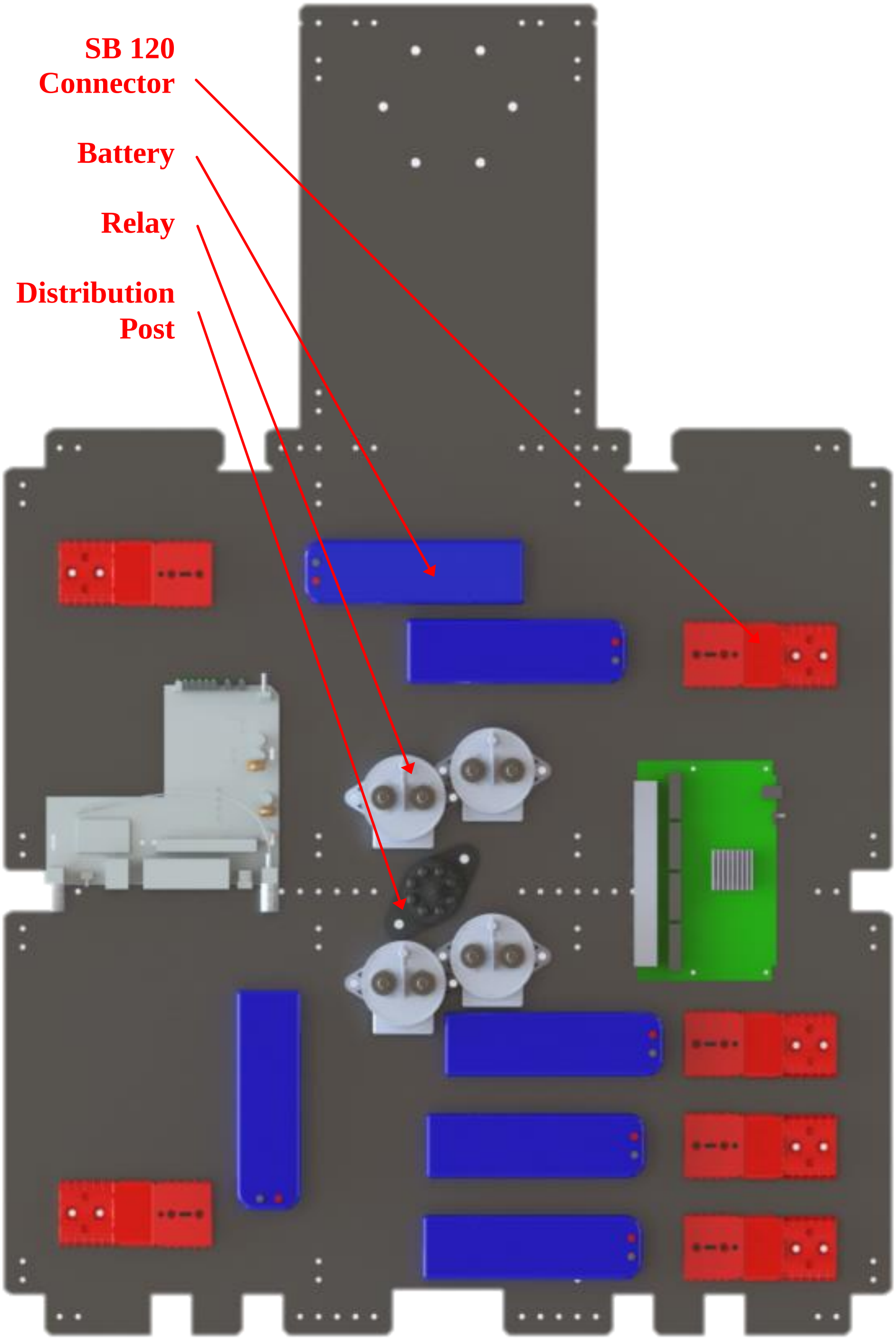

Figure 5.11: Power Distribution Layout

Each of CERES modules has varying needs (Table 5.3) for regulated power. While requirements may differ, the DROK DC to DC Buck Converter [50] can be adapted to meet each module's individual needs. This regulator, shown in Figure 5.12, offers a wide input range of 4-32 volts, an adjustable voltage output range of 1.2-32 volts, and continuous output of 10 amps with a peak of 15 amps for short periods of time. When a module requires more than 10 amps or has multiple voltage requirements, additional regulators can be added to meet those requirements.

Figure 5.12: DROK DC to DC Buck Converter [50]

Table 5.3: Regulator Requirements

Module	**Quantity**	**Requirement**	**Max Current Draw**
Drivetrain	1	12 V	9 A
Localization	1	12 V	5 A
	1	7 V	10 A
Sample Detection	1	12 V	4 A
Acquisition	3	12 V	38 A
	1	7 V	5 A

5.3.1.2 Computing

Similar to the power hardware, the different modules share commonality among the computing systems. Each of the modules utilizes a model of NVIDIA’s Jetson Tegra development boards and identical USB hubs to support expansion.

These development boards (Figure 5.13) make for a very practical embedded computing platform because of their low power consumption, small form factor, and low weight. Integrated GPUs allow for hardware acceleration for image processing algorithms and make these boards a great choice for this application. Each module is controlled with a Tegra K1 (TK1) development board except for the Localization module. The Localization module utilizes the more powerful Tegra X1 (TX1) development board to assist in its resource intensive image processing tasks. The distributed computing architecture allows for heavier software loads of a particular module to be shared across platforms if needed, providing increased flexibility.

The Tegra K1 SoC features the NVIDIA Kepler GPU with 192 GPU CUDA cores and an NVIDIA 4-Plus-1 quad-core ARM Cortex-A15 CPU. This development board is equipped with two gigabytes of RAM and 16 gigabytes of flash memory. SDIO and SATA connections support options for expandable memory. Some of the peripheral interfaces include HDMI, USB 3.0, RS232, PCIe, and a gigabit Ethernet connection. The TK1 offers an expansion port to provide GPIO, UART, i^2C, and several other interfaces [51].

The Tegra X1 SoC features the NVIDIA Maxwell GPU and quad-core ARM Cortex-A57 CPU. This development board is equipped with four gigabytes of LPDDR4 RAM. Sixteen gigabytes of eMMC 5.1 flash memory is also available. SDIO and SATA connections support options for expandable memory. A larger addressing capacity is supported for SD3.0 and SD-XC cards up to two terabytes. An ample amount of peripheral interfaces are supported. Some of those interfaces include USB 3.0, HDMI, UART, PCIe, I^2C, and GPIO connections. WiFi, Bluetooth and gigabit Ethernet connectivity is also supported. [52]. A comparison of the two development boards can be seen in Table 5.4.

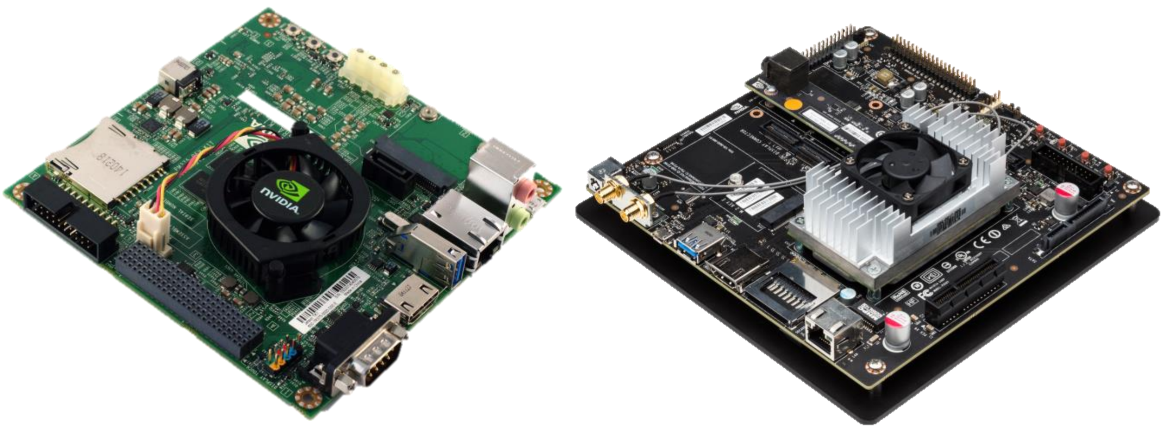

Figure 5.13: Tegra K1 (left) and Tegra X1 Development Boards (right) [53] [54]

Table 5.4: Development Board Characteristics

Module	**TK1**	**TX1**
Size (LxWxH)	12.7cm x 12.7cm x 2.7cm	17cm x 17cm x 3.5cm
Weight	140 g	330 g
CPU	Cortex-A15	Cortex-A57
CPU Cores	Quad + 1	Quad
Clock Frequency	2.2 GHz	1.73 GHz
GPU	Kepler	Maxwell
GPU Cores	192	256
GFLOPS	325	1024
RAM	2 GB	4 GB
Flash	16 GB	16 GB
Expandable Memory	SD/MMC & SATA	SDIO & SATA

With a limited number of USB connections provided by the Tegra boards, each module needs a method to provide support for multiple USB devices. Providing support for multiple USB devices enhances the flexibility and adaptability of the system. The Amazon 7-port USB 3.0 Hub [55] provides the ability for expansion. USB 3.0 hubs ensure each device connected can receive the proper amount of bandwidth. The USB hub (Figure 5.14) is a powered hub and is powered at 12 volts. A powered hub ensures an adequate supply of power to any additional downstream devices that may be added to the system.

Figure 5.14: 7-Port USB Hub [55]

5.3.2 Drivetrain Module

The Drivetrain module is responsible for supporting locomotion, obstacle detection, communication, and safety. As the most complex and intricate system on CERES, this module is mission-agnostic and supports only the most basic and universal functions that are required by all rovers. An annotated render of CERES with the Drivetrain hardware can be seen in Figure 5.15 and layout of the electronics shelf can be seen in Figure 5.16. Electrical schematics that detail system wiring can be found in Figure A.2 of Appendix A.

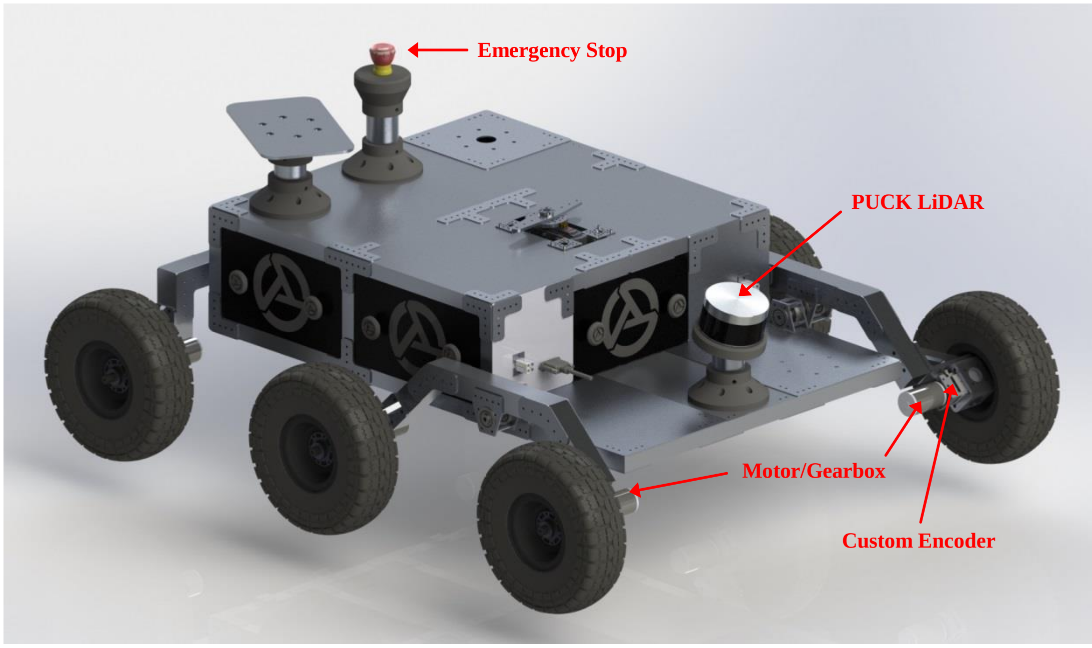

Figure 5.15: CERES Platform with Drivetrain Hardware

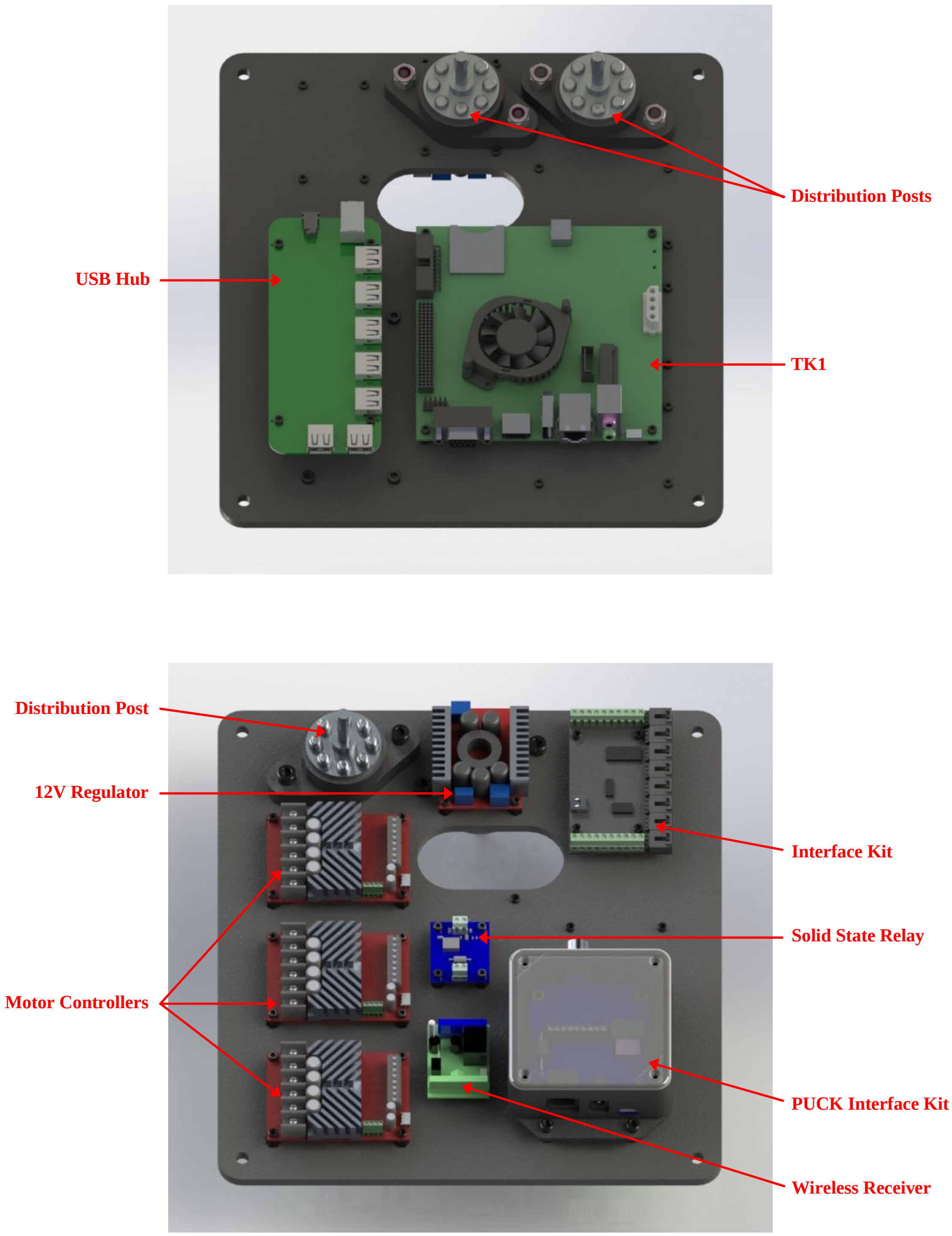

Figure 5.16: Top (above) and Bottom (below) View of the Drivetrain Electronics Shelf

5.3.2.1 Locomotion

CERES achieves mobility by independently controlling six wheels. Lacking the mechanisms needed for explicit steering, CERES drives via skid-steering. Each of the six drive wheels are driven by a 12 volt, sealed, DC BAG motor [56]. Each BAG motor has a rated maximum power output of 147 watts and a maximum stall current of 41 amps. Interfacing to a customizable three-stage VersaPlanetary gearbox [57], each motor-gearbox combination (Figure 5.17) has a gear ratio of 150:1 and can output 59 newton-meters.

Figure 5.17: Vex BAG Motor and VersaPanetary Gearbox Combination [57]

The six main drive wheels are driven by three RoboClaw ST 2x45A motor controllers [58]. Each dual-channel motor controller can continuously supply up to 45 amps per channel and has a wide operating voltage of 6-34 volts. Supporting a variety of communication interfaces, each motor controller is accessed over USB via a micro-USB interface. Power is transferred from the motor controller terminals to the motor via a series of PP45 quick disconnect connectors [59] at the electronics enclosure and at the motor. This allows for easy detachment and replacement in the event of a hardware failure or mechanical design changes.

RoboClaw motor controllers (Figure 5.18) support dual feedback inputs for closed-loop PID control. PID speed control support is crucial to help maintain constant speed as CERES traverses steep grades and encounters obstacles. This control also mitigates problems associated with lower overall battery voltages as drive time increases. Having hardware PID support with auto tuning features significantly reduces development time over building and implementing a software solution. Speed control with quadrature encoders allows for sensing of up to 19.6 million encoder pulses per second.

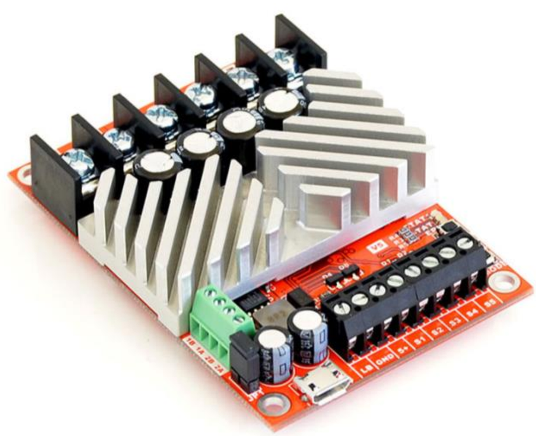

Figure 5.18: Ion Motion Control RoboClaw ST 2x45A Motor Controller [58]

Each motor-gearbox combination on CERES has an integrated custom encoder circuit. The Allegro MicroSystems Hall effect sensor features a dual differential output that provides both speed and direction [60]. After drilling a hole in the input stage of each gearbox, the encoder bolts to the side of the gearbox and senses each tooth of the gear on the output shaft of the motor. Power and data lines from screw terminals on the custom encoder PCB interface back to the electronics enclosure via a custom DB9 connector. From the DB9 bulkhead connector on the electronics box, power and data lines interface directly to screw terminals on the motor controller. The encoder receives power directly from a 5 volt source on the motor controller. A picture of the custom encoder PCB can be seen in Figure 5.19 and the electrical schematic can be seen in Figure A.6 of Appendix A.

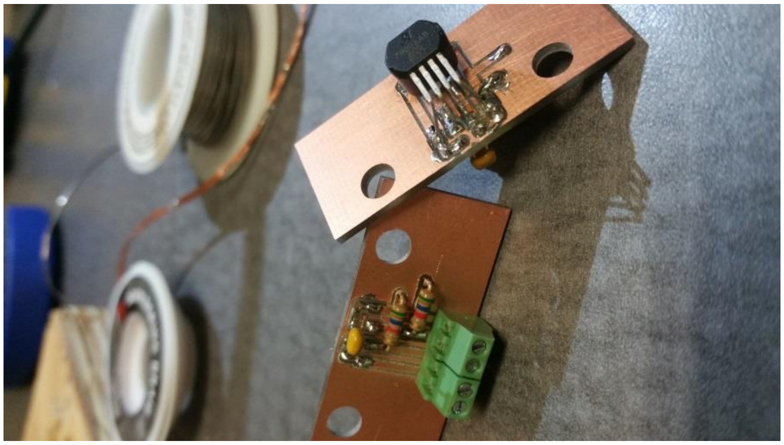

Figure 5.19: Custom Encoders

5.3.2.2 Obstacle Detection

Obstacle detection is achieved through the use of the PUCK 3D LiDAR sensor. With a measurement range of up to 100 meters and an adjustable rotational rate, the PUCK can return up to 300,000 data points per second. By identifying a ground plane in the returned point cloud data using a RANSAC algorithm [61], objects in the field-of-view that protrude above the ground plane can be positively identified as obstacles. To achieve this, the PUCK utilizes 16 laser channels spread across a 30 degree vertical field-of-view and 360 degree horizontal field-of-view. The PUCK (Figure 5.20) is powered at 12 volts and operates nominally at 8 watts. The PUCK returns its point cloud information via an Ethernet connection to the switch.

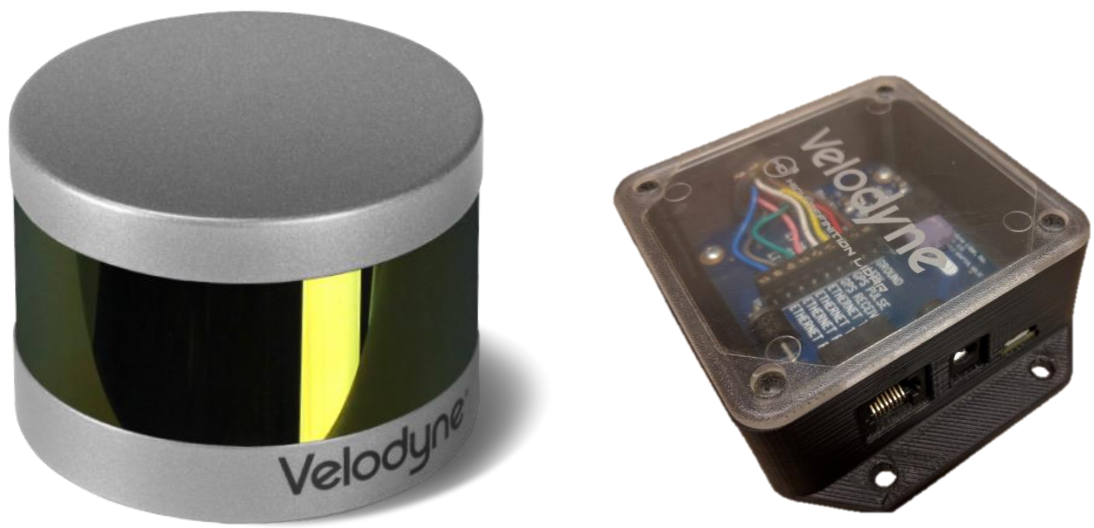

Figure 5.20: PUCK LiDAR (left) and Interface Kit (right) [62]

5.3.2.3 Communication

The Drivetrain module is responsible for supporting inter-module communication. Modules interface with each other via a standard Ethernet connection. The NETGEAR GS108 Switch provides support of up to 8 Ethernet connections at gigabit speeds. This switch operates at 12 volts and has a max power consumption of approximately 5 watts.

To facilitate wireless communication to a remote operations area, CERES carries a 2.4 GHz wireless router on-board. Since human interaction with the robot during the SRRC is not permitted, this router is removed before competition. However, during development and testing, the router is essential for testing, monitoring, debugging, and flashing code. External wired communication to modules is also made available via an Ethernet port on the electronics enclosure that connects directly to the switch. Both communication devices can be seen in Figure 5.21.

Figure 5.21: NETGEAR GS108 Gigabit Switch (left) and Linksys WRT54G Router (right) [63] [64]

5.3.2.4 Safety

Competition rules state that each robot much be equipped with a safety light, pause switch and emergency stop. The E-stop ensures that all robot operation can come to an immediate halt in the event of undesirable or uncontrolled operation. The E-stop performs this task by controlling the operation of power relays on the individual modules of CERES. When the button is pressed, an open circuit is created across all the relays immediately severing all power to the modules. A diagram illustrating the operation can be seen in Figure A.1 of Appendix A. The E-stop button is a high visibility, red, mushroom design (Figure 5.22). Once depressed, the E-stop button will remain off until manually reset. Upon restart after an E-stop event, the rover will require time for a complete power-up operation.

Figure 5.22: Emergency Stop Button

The wireless pause capability affords judges the opportunity to pause a robot during operation to prevent any collisions or any possible damage to a robot. The wireless pause switch for CERES utilizes a small, lightweight, and convenient one-button handheld transmitter [65]. Operating at 315 MHz and with a theoretical range of 2000 meters, the handheld transmitter is powered by a 9 volt battery. This transmitter interfaces with a 4 Relay DC Wireless Remote Receiver [66]. The receiver is powered at 12 volts and is rated up to 28 volts and 10 amps per channel. An external antenna is incorporated to increase operating range. While the momentary button is pressed on the transmitter, an LED on the transmitter illuminates and the normally open terminals on the receiver's relay close. The detection of this switch transition is used to stop all movements of the robot. To resume normal operation simply press the transmitter button once more. This hardware can be seen below in Figure 5.23.

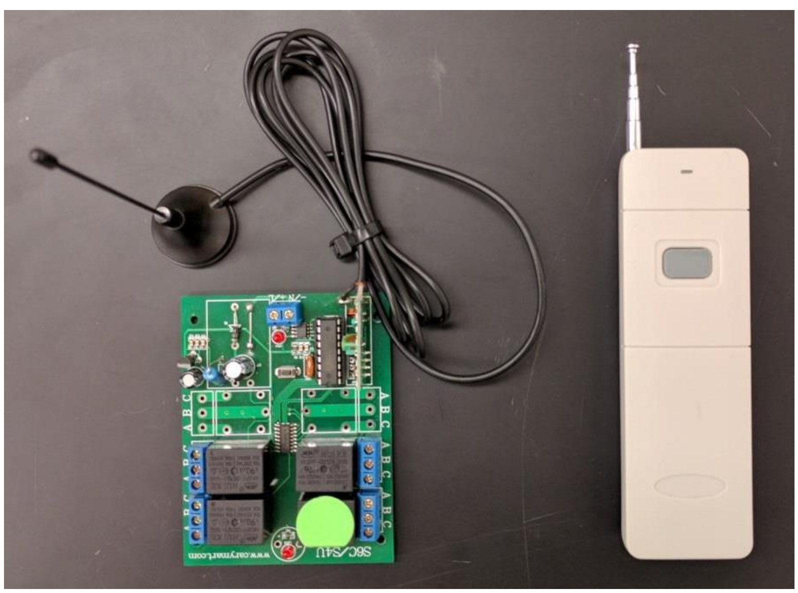

Figure 5.23: Wireless Transmitter (left) and Reciever (right)

The safety light indicates the robot’s state of operation to everyone around the robot. The safety light is a 7440 form factor amber LED bulb [67]. The light contains 36 individual LEDs, is powered at 12 volts, and operates nominally at 3 watts. The 1 hertz flash rate, required during autonomous operation, is achieved through the use of the PhidgetsInterfaceKit 8/8/8 [68] and a Phidgets Solid State Relay Board [69] (SSR). The interface kit generates the signal that controls the SSR providing power to the light. The interface kit communicates to the TK1 over USB 2.0 and generates a 5 volt output signal to control the SSR. These safety equipment components can be seen in Figure 5.24 and Figure 5.25.

Figure 5.24: Safety Light [67]

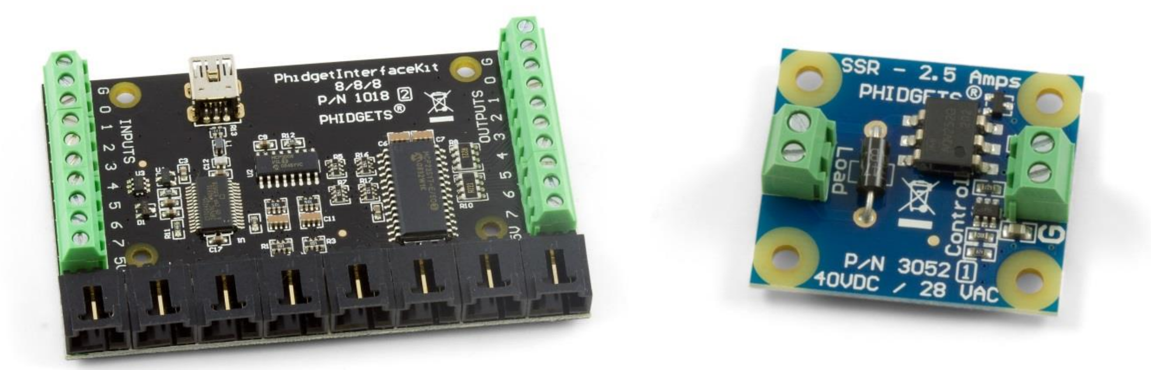

Figure 5.25: Phidgets PhidgetsInterfaceKit 8/8/8 and Solid State Relay Board [68] [69]

5.3.3 Localization Module

The Localization module is responsible for supporting the robot's ability to determine its pose within the competition arena. Localization is achieved through a combination of sensors and supporting hardware and is primarily a vision-based system. Vision is achieved with a stereo camera mounted to a dual axis gimbal. An inertial measurement unit (IMU) provides orientation information about CERES and assists with odometry measurements. Orientation information is used to manipulate the gimbal. An annotated render of CERES with only the Localization hardware can be seen in Figure 5.26 and layout of the Localization electronics shelf can be seen in Figure 5.27. Electrical schematics that detail system wiring can be found in Figure A.3 of Appendix A.

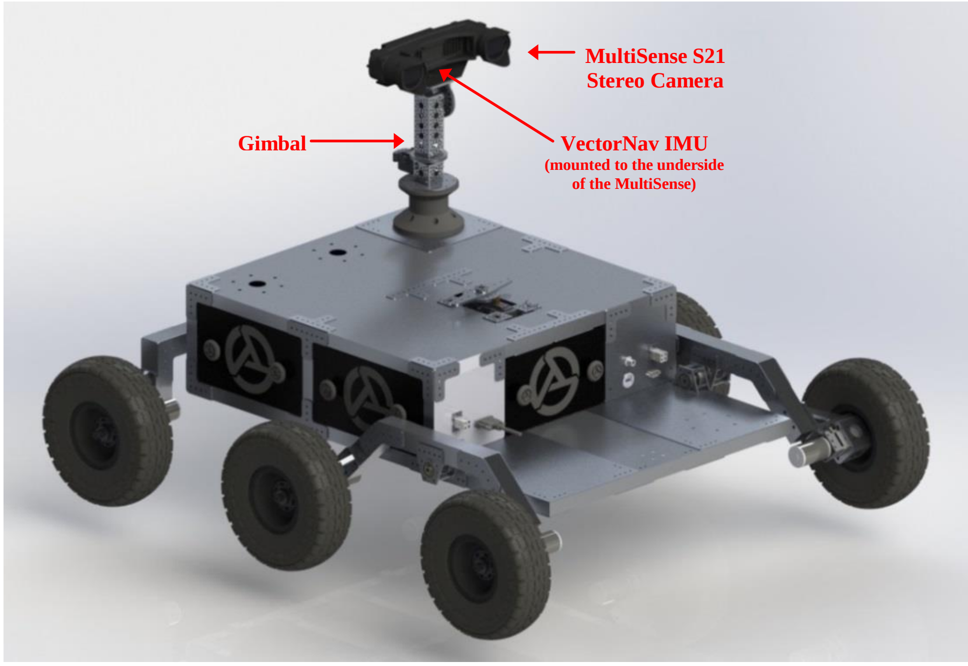

Figure 5.26: CERES Platform with Localization Hardware

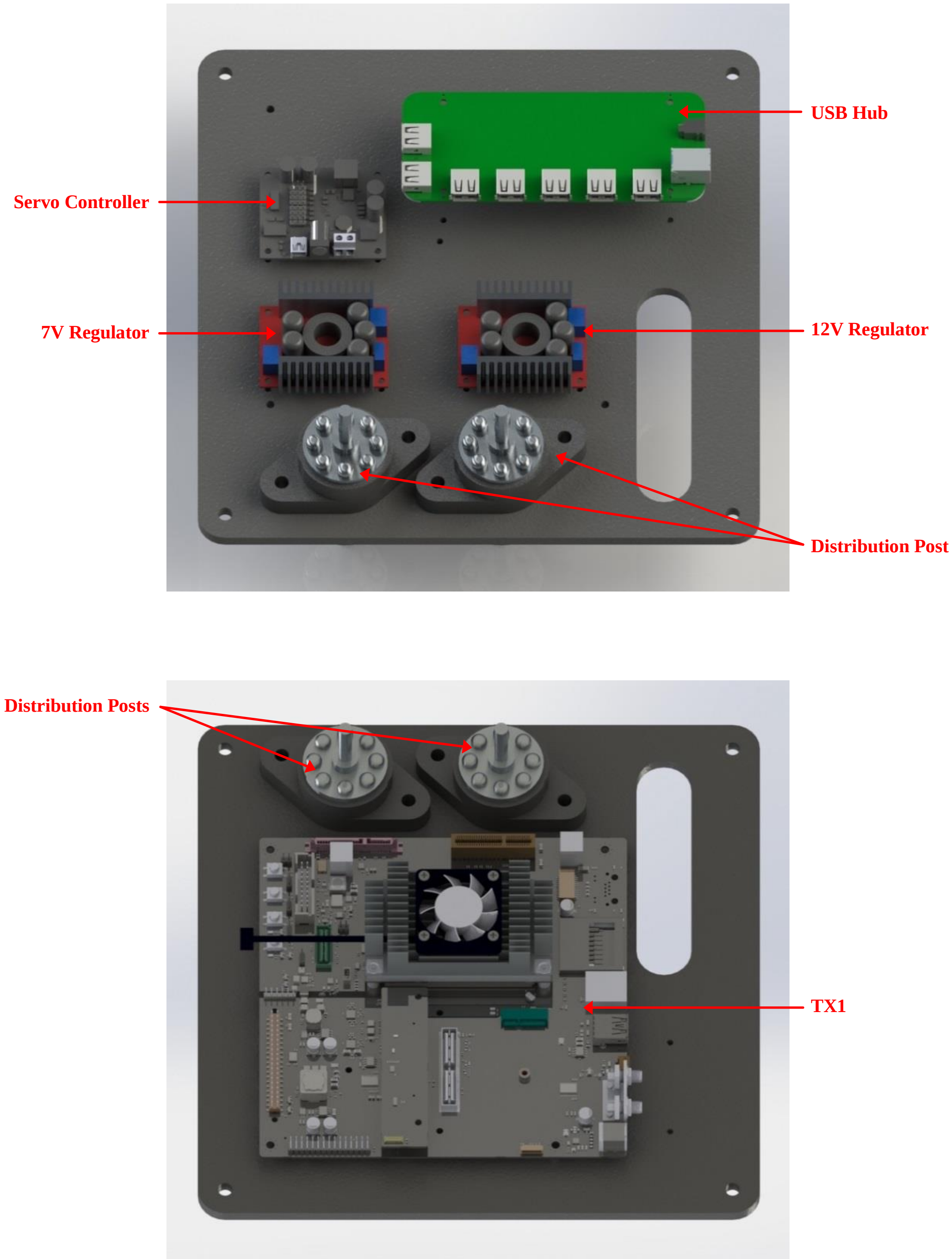

Figure 5.27: Top (above) and Bottom (below) View of the Localization Electronics Shelf

Localization's primary goal is to maintain a constant understanding of the robot's location within the arena. To achieve this, CERES utilizes the MultiSense S21 Stereo Camera [70]. The S21 is highly customizable, features five different focal length options, two imager options, and three different picture resolution outputs from which to choose. For this competition, the S21 is configured with a 12.5 millimeter focal length and CMV4000 4 megapixel, global shutter, imager. This allows for a 48 degree x 48 degree field-of-view and operates at up to 15 frames per second. This focal length produces an approximate accuracy of +/- 0.5 meters at a distance of 45 meters. The S21 (Figure 5.28) has an on-board IMU and incorporates pulse-per-second support for external triggering and time synchronization [71]. The camera can simultaneously output the color and 3D position of each of the 15 million pixels generated per second. The on-board generation of disparity maps provides hardware acceleration and reduces the software work load. This sensor is typical of those that are producing increasingly large amounts of data justifying the need for improved processing speed and additional memory. The S21 operates at 12 volts and has a nominal power draw of 12 watts. The S21 returns its point cloud information via an Ethernet connection to the switch.

Figure 5.28: Carnegie Robotics MultiSense S21 Color Range Sensor [70]

To keep the MultiSense pointed in the direction of the home beacon as CERES traverses the arena, the S21 sits atop a dual axis gimbal (Figure 5.29). The localization gimbal is operated by dual Hitec HS-7950TH servos [72] (Figure 5.30). These servos offer titanium gears and increased torque allowing them to support the approximately two kilogram weight of the stereo camera when standard servos would fail under such a load. Integrated potentiometers allow for precise control. These servos operate at 7 volts and are controlled by PWM signals that are generated from a Phidgets PhidgetAdvancedServo Controller [73]. The servo controller (Figure 5.31) is powered and communicates via a 5 volt, USB 2.0 connection from the compatible USB 3.0 hub.

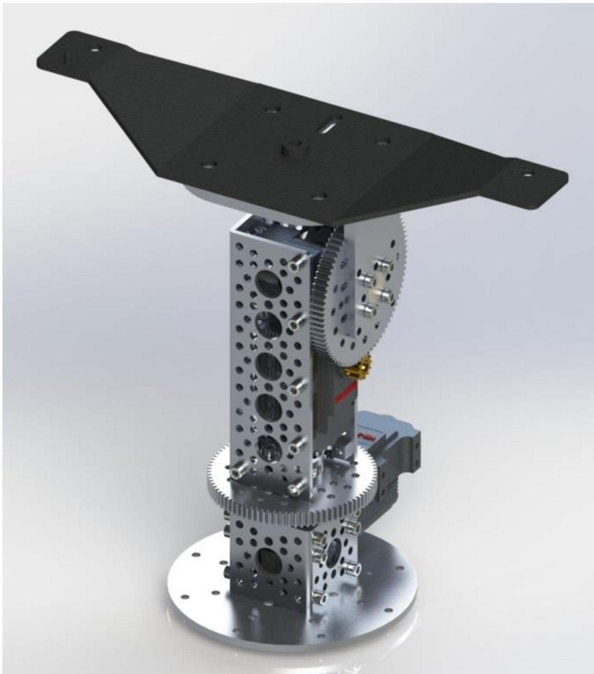

Figure 5.29: Dual Axis Gimbal for MultiSense S1 Stereo Camera

Figure 5.30: Hitec HS-7950TH Servo [72]

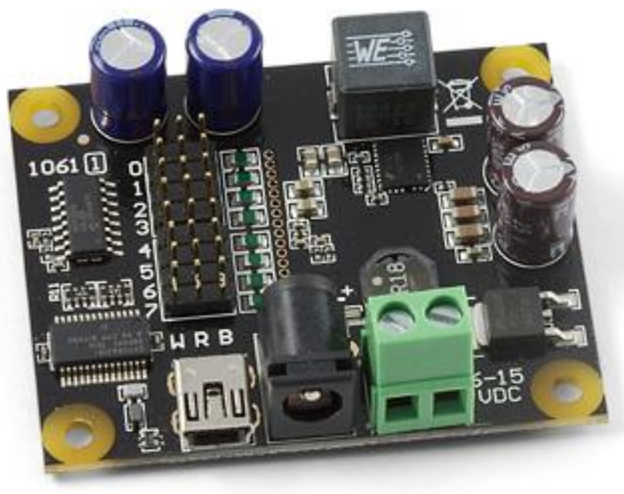

Figure 5.31: Phidgets PhidgetAdvancedServo 8-Motor Controller [73]

The Localization module also has a VectorNav VN100 Rugged IMU mounted on-board to help keep the camera level and oriented toward the beacon during operation. A secondary function is to provide odometry data that assists with path planning algorithms. The VN100 is a 10-axis MEMS IMU, features update rates up to 300 hertz, and offers a quaternion based, drift compensated Kalman filter. This IMU (Figure 5.32) is powered and communicates to the TX1 from the USB hub via an FTDI USB-RS232 conversion cable [74].

Figure 5.32: VectorNav VN100 Rugged IMU [75]

The Localization module utilizes a TX1 as its computing platform. This platform interfaces to various Localization components as well as CERES' other modules through USB 3.0 and gigabit Ethernet connections. The 7-port USB 3.0 hub allows for multiple USB connections to the TX1. The TX1 and USB hub are powered at 12 volts.

5.3.4 Sample Detection Module

The Sample Detection module is responsible for actively searching, detecting, and identifying samples in the competition arena. An annotated render of CERES with only the Sample Detection hardware can be seen in Figure 5.33 and layout of the electronics self can be seen in Figure 5.34. Electrical schematics that detail system wiring can be found in Figure A.4 of Appendix A.

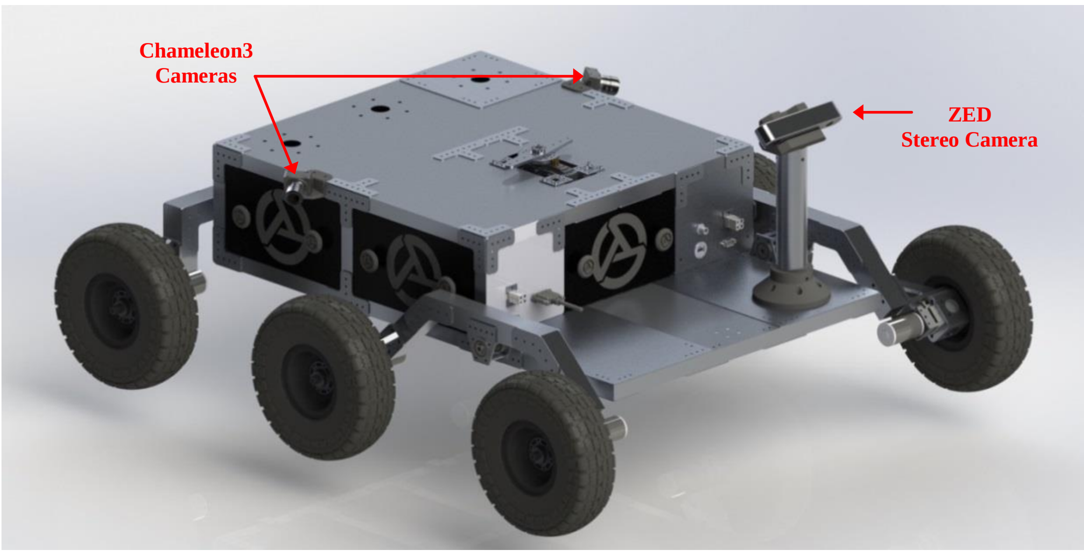

Figure 5.33: CERES Platform with Sample Detection Hardware

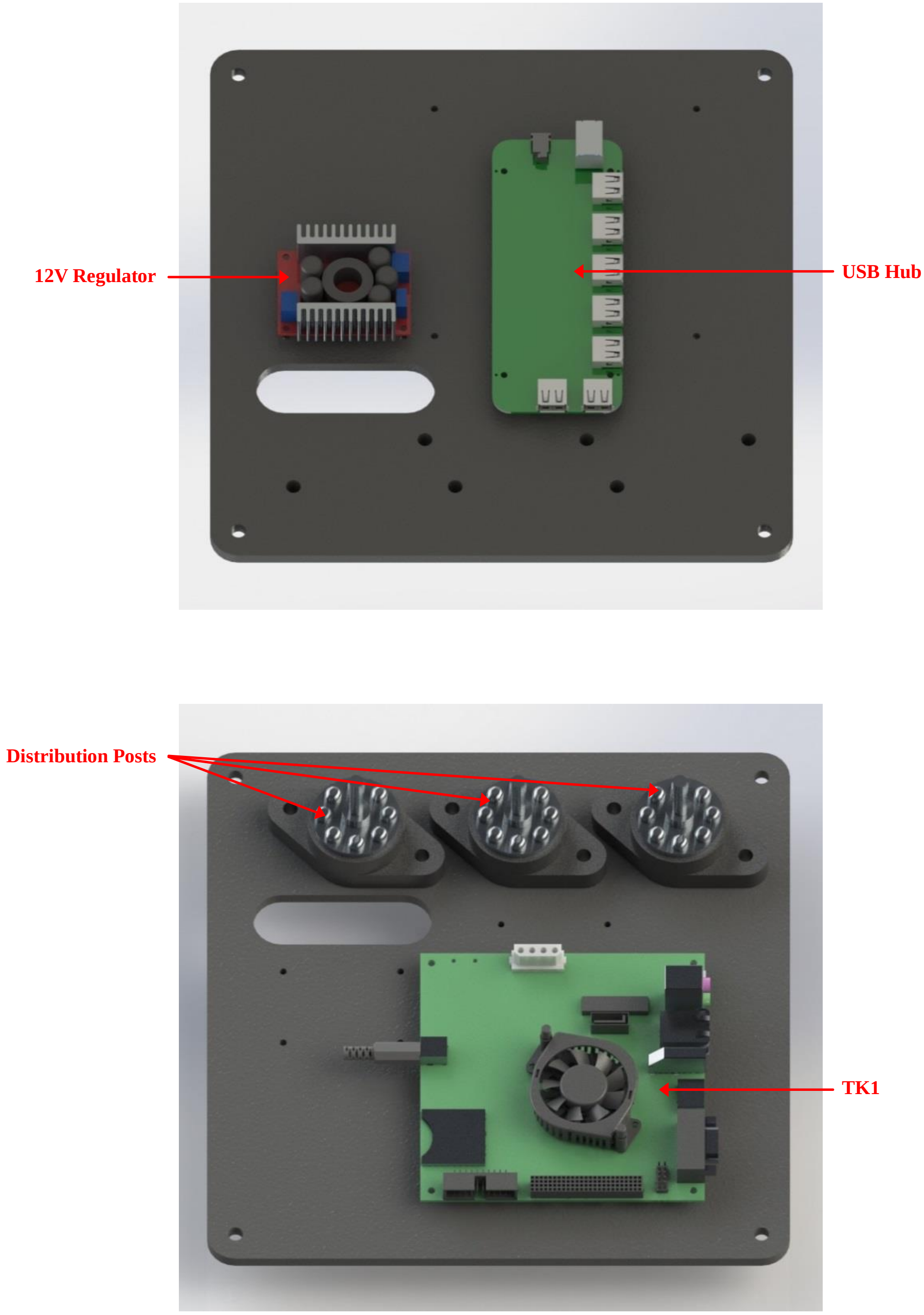

Figure 5.34: Top (above) and Bottom (below) View of the Sample Detection Electronics Shelf

Similar to localization, CERES takes a visual approach to sample detection. Two Point Grey Chameleon 3 mono cameras are used. These cameras, shown in Figure 5.35, use algorithms to detect the distinct colors of the samples. Once a sample is detected, the robot is dispatched to the general area of the sample. Chameleon3 cameras are both powered and communicate over a USB 3.0 interface. The global shutter imager produces a 1.3 megapixel color image and operates at 149 frames per second. Twelve different data formats are supported [76].

Figure 5.35: Point Grey Chameleon3 Camera (left) and 8mm Lens (right)

Running the same color detection algorithm, a Stereolabs ZED stereo camera (Figure 5.36), mounted to the front of CERES, is used to seek out samples. After a sample is initially detected by either the Chameleon3 cameras or the ZED, the ZED takes over to provide a more precise sample location. At up to 100 frames per second and with a four megapixel resolution, the ZED can provide millimeter accuracy of a sample's location. With an operational range of 70 centimeters to 20 meters, the ZED is elevated above the chassis of CERES to provide an adequate field-of-view [77].

Sample Detection benefits the most from redundancy. This redundancy is provided multiple ways. By spreading the sample search algorithm among three cameras, triple redundancy is achieved at the sensor level. This scalable system allows for even higher levels of redundancy with each additional camera. Should any one camera fail, remaining cameras are able to continue searching. The ZED is actually powered and communicates from the Acquisition module. This provides a dual layer of redundancy should a power or computer failure prevent either module from functioning. Together, these methods greatly enhance system reliability.

Figure 5.36: Stereolabs ZED Stereo Camera [77]

5.3.5 Acquisition Module

The Acquisition module is responsible for supporting sample localization, sample acquisition, and sample containment. An annotated render of CERES with only the Acquisition hardware can be seen in Figure 5.37 and layout of the electronics shelf can be seen in Figure 5.38. Electrical schematics that detail system wiring can be found in Figure A.5 of Appendix A.

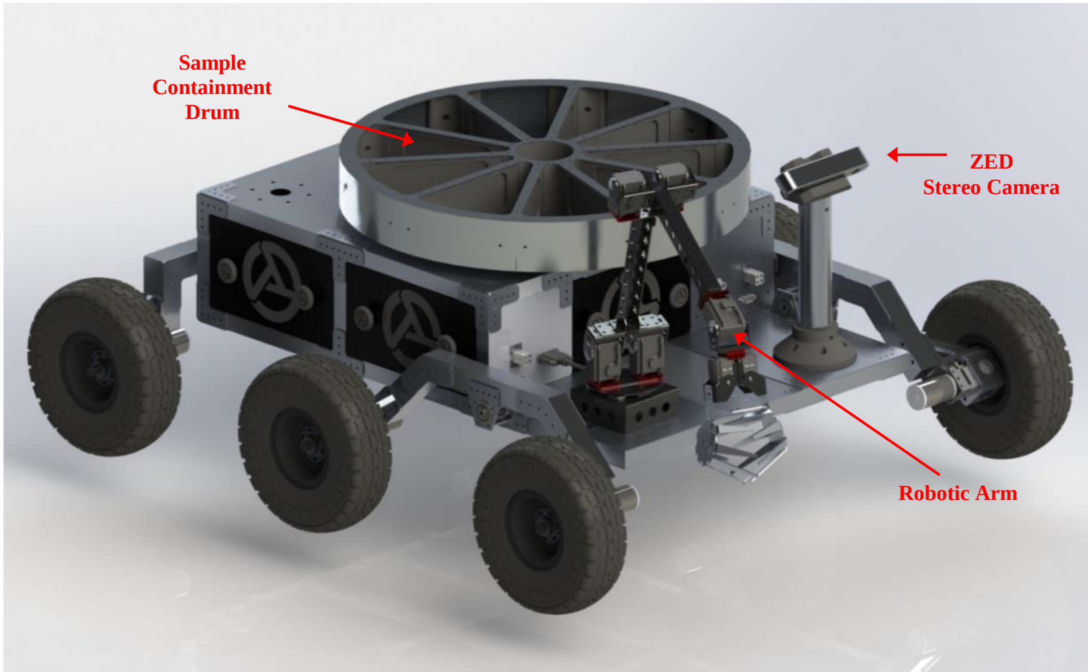

Figure 5.37: CERES Platform with Acquisition Hardware

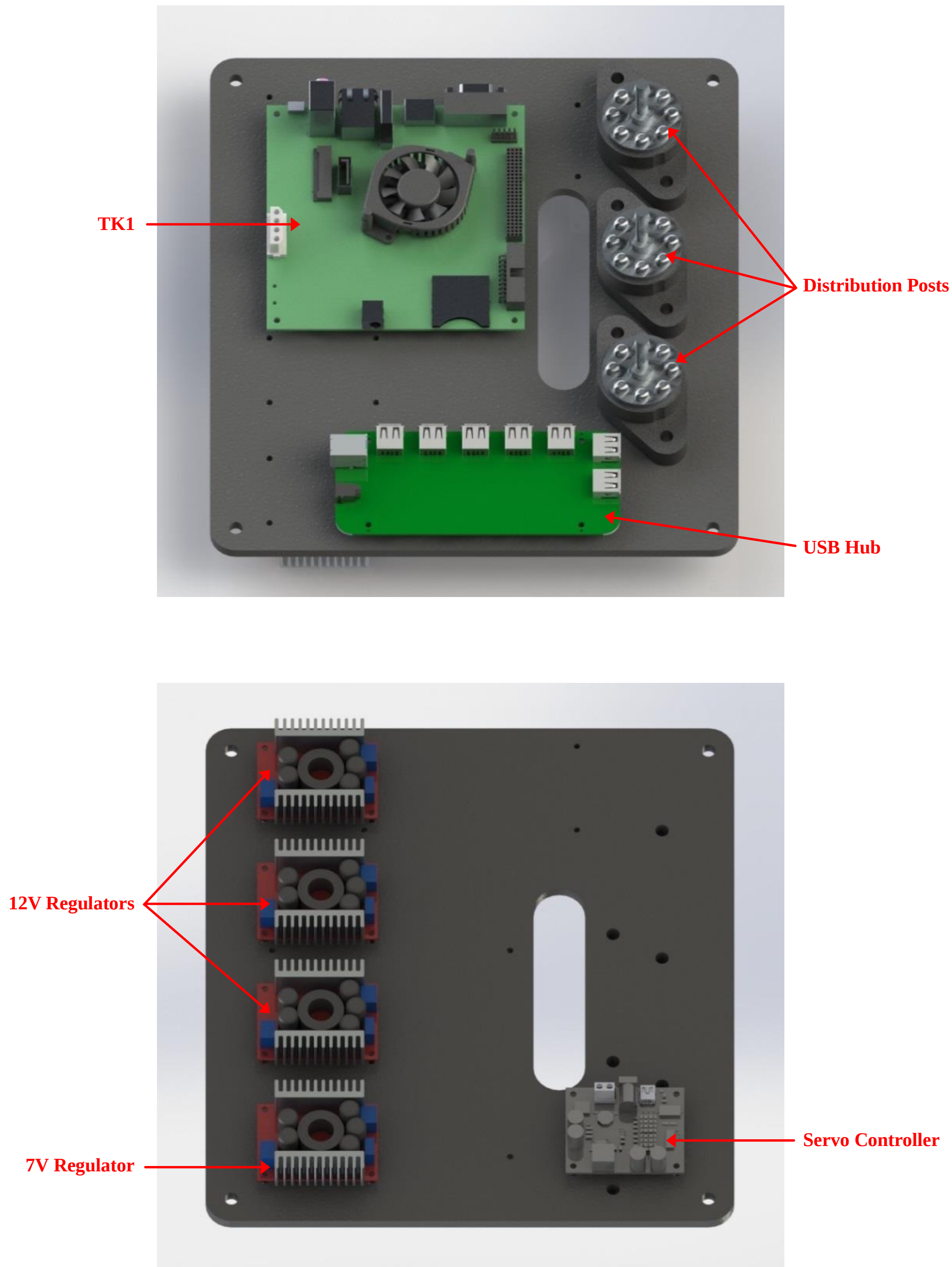

Figure 5.38: Top (above) and Bottom (below) View of the Acquisition Electronics Shelf

5.3.5.1 Sample Localization

The first step in sample acquisition involves sample localization. CERES must be able to accurately relay the position of a sample to the arm for collection. Once CERES finds and properly aligns with a sample, the ZED stereo camera, mentioned in section 5.3.4, is used to determine the sample's location relative to the base of the robotic arm. Sample location coordinates within the camera's coordinate system are transposed to the arm's coordinate frame and are passed from the ZED to the robotic arm for sample acquisition.

5.3.5.2 Sample Acquisition

The second step in sample acquisition involves collecting the sample. CERES utilizes a custom configuration of the CrustCrawler Pro-Series Robotic Arm (Figure 5.39) mounted on the front of CERES, opposite of the ZED; the arm operates with five degrees-of-freedom. These five degrees-of-freedom are achieved using a turntable, a shoulder, an elbow, a wrist, and an end effector. The wrist manipulates a custom designed end effector. Samples are collected using inverse kinematic solutions that dispatch the arm along pre-defined paths.

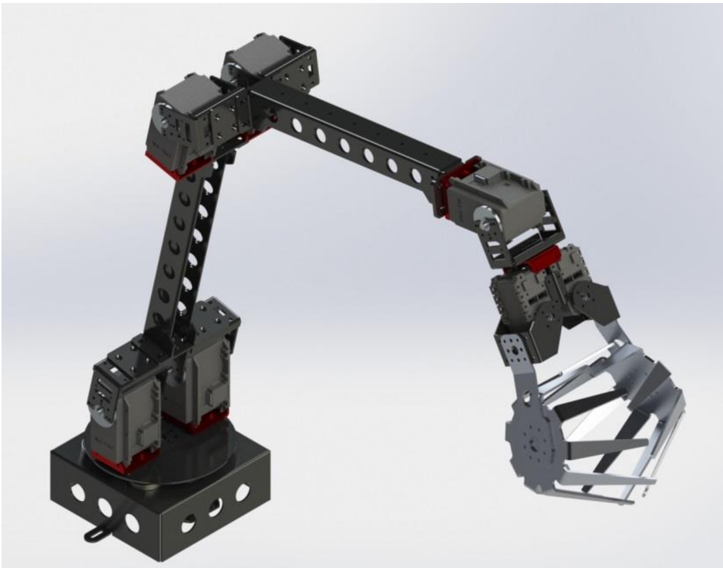

Figure 5.39: CrustCrawler Pro-Series Robotic Arm

The arm is controlled with AX and MX series Dynamixel actuators (Figure 5.40). These actuators provide position, temperature, load, and voltage feedback and have numerous protection features. A programmable LED interface allows for rapid debugging during testing. PID control is also supported [78]. Table 5.5 shows a comparison of the each of the servos used to control the robotic arm.

Figure 5.40: Dynamixel Servos AX-18A (left), MX-64T (middle), and MX-106T (right) [79] [80] [81]

Table 5.5: Robotic Arm Servo Comparison

Actuator	**Quantity**	**Stall Current**	**Stall Torque**	**Resolution**	**Weight**	**Use**
AX-18A [79]	2	2.2 A	1.8 N·m	0.290°	54.5 g	Gripper
MX-64T [80]	1	4.1 A	6.0 N·m	0.088°	126.0 g	Turn Table
MX-106T [81]	5	5.1 A	8.4 N·m	0.088°	153.0 g	Shoulder/Wrist/ Elbow

These actuators allow for daisy chaining of power and communication. However, bench testing indicated that daisy chained power did not provide adequate current for high-current movements of the arm. Specifically, servos near the end of the chain were starved of current due to current limits implemented by servos closer to the power supply. In this case, the shoulder joint limited the current available to the rest of the arm. To provide adequate power for over-current events, each actuator is powered individually via a power bus while communication remains daisy chained. The gripper actuators that control the end effector are the only actuators that use daisy chain power. A custom DB15 breakout connector is used to carry power and data from the electronics shelf to the arm. Communicating with a half-duplex asynchronous serial communication, the Xevelabs USB2AX v3.2a USB to TTL Dynamixel Servo Interface (Figure 5.41) [82] is used to control the arm.

Figure 5.41: Xevelabs USB2AX v3.2a USB to TTL Dynamixel Servo Interface [82]

5.3.5.3 Sample Containment

The final step in acquiring a sample is sample storage. CERES carries a sample containment drum on-board, shown in Figure 5.42. This circular drum contains ten individual compartments and each compartment is large enough to contain any one sample. As per the rules, samples may not come in contact with each other. This prevents contamination of samples on real-world rovers. Individual compartments in the drum prevent any sample contamination. Once a sample is successfully captured, the arm is then dispatched to a pre-defined location above the sample containment drum. The end effector opens, releasing the sample, and the sample falls into the selected slot on the drum. The open top allows for easy deposition and removal of samples. Once a sample is securely placed in the sample containment drum, the drum is rotated to align a new empty compartment in preparation of the next sample to be collected.

The sample containment drum must rotate to allow for the collection of multiple samples. The sample containment drum is rotated in increments of 36 degrees. This rotation is controlled using a Hitec HS-7950TH servo and controlled using a Phidgets PhidgetAdvancedServo Controller. This servo/controller combination is the same hardware configuration used on the Localization gimbal. Potentiometer feedback, incorporated into the servo, allows for precise control of the drum.

Figure 5.42: Sample Containment Drum

5.4 CERES Software

CERES uses software that includes many custom algorithms and functions developed in-house. However, CERES uses an off-the-shelf distributed software operating system, called the Robot Operating System (ROS), which coordinates computing activities across all its modules. ROS was chosen specifically because of its message passing communication infrastructure among the various ROS software nodes distributed among the modules. The Ethernet-based interconnection network facilitates easy message passing among these ROS nodes.

5.5 Benefits of MAARS Implementation

The modularity of the system was found to be extremely beneficial. It was beneficial during the design process, during development, and during system integration and testing. The modularity allowed for wide spread hardware reuse and provided high levels of maintainability and flexibility through reconfiguration and scalability. During development of the Sample Detection module, the module's computing platform was damaged and could no longer be used. Redundant, distributed computing platforms allowed the Sample Detection module's software workload to be easily transitioned to the Acquisition module. By utilizing common batteries among modules, the batteries could be used for and were easily swapped among the modules. System reconfigurability provided a level of flexibility and redundancy by using the PUCK for sample detection when cameras were not functional. The implementation of the modular design allowed easy access to hardware to diagnose problems and change batteries during testing and development. The scalable nature of the modules easily allowed for an increased number of cameras on the Sample Detection module to provide a larger coverage area when searching for samples.

5.6 Competition Results

Before competing in the two hour competition described in Section 5.1, CERES had to first pass a pre-inspection phase and a Level 1 task. Pre-inspection was used to demonstrate a robot's functionality while Level 1 served as a subset of the two hour competition. Successfully completing both pre-inspection and Level 1 granted eligibility to attempt Level 2, the two hour competition [43]. CERES successfully collected the pre-cached sample from a distance of 20 meters and returned it back to the landing site to complete pre-inspection requirements. During Level 1, CERES successfully returned the required pre-cached and easy samples in six minutes and four seconds, easily beating the 30 minute deadline. This was the fastest recorded completion time. As one of only seven teams to complete Level 1 in the competition's five year history, CERES was the first to pass Level 1 in its first year. During Level 2, CERES encountered a hardware failure resulting in the collection of no samples. A picture of CERES final configuration can be seen in Figure 5.43.

Figure 5.43: CERES Final Configuration

CHAPTER 6

CONCLUSIONS

6.1 Conclusions

This thesis presents MAARS, a Modular Architecture for Autonomous Robotic Systems. This scalable and modular design can support any number of hardware modules that can be added, removed, or reconfigured without adversely impacting the functionality of other modules. The architecture was successfully implemented on the CERES platform as part of the University of Alabama's submission in the 2016 NASA SRRC. The modularity and the scalability of the architecture were found to be beneficial. Modules were removed and reconfigured during times of hardware failures or design changes. The modularity allowed for relatively quick and easy removal of components from the system while the scalability allowed for additional system development, testing, and debugging to proceed without infringement.

6.2 Future Work

The MAARS architecture, and more specifically the implementation of it, could benefit from several improvements. One of these improvements would be the addition of a health monitoring module. Such a module could include integrated power monitoring, hardware status reports and fault protection limits. Integrated power monitoring would serve two purposes. First, batteries would no longer be susceptible to over discharge cycles during operation. Second, real-time power data could be factored into the autonomous decision making. Operational parameters would no longer be strictly based on time but rather on available power as well. Hardware status reports would allow for both the system and the user to know what hardware is functional and available.

In the event of a failure, the system could react and mitigate possible mechanical damage or allocate certain tasks to other systems in the event of a sensor failure. Finally, fault protection limits, in both hardware and software, would further add to the robust and successful operation of the system. Circuit breakers, fuses and other dedicated hardware could prevent inadvertent damage to batteries and electronics from short circuits and reverse polarity. Software limits could prevent over current conditions on drive motors and help avoid roll over conditions on steep grades.

Additional improvements to the implementation would further enhance the architecture's true modular and scalable qualities. Standardization of the computing platforms across modules would have increased the flexibility and reusability of the system as a whole. The creation of a backplane for both power and communication connections would eliminate the need for several independent connection points. A backplane would also add a level of convenience when servicing a module.

Finally, MAARs could further benefit and improve from analysis gathered during the implantation in new case studies. A sample return rover was presented in this thesis but this design could extend to other rover-based missions, satellite and unmanned aerial vehicle operations, and many other embedded system applications.

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APPENDIX A

ELECTRICAL SCHEMATICS

A.1 System Schematic

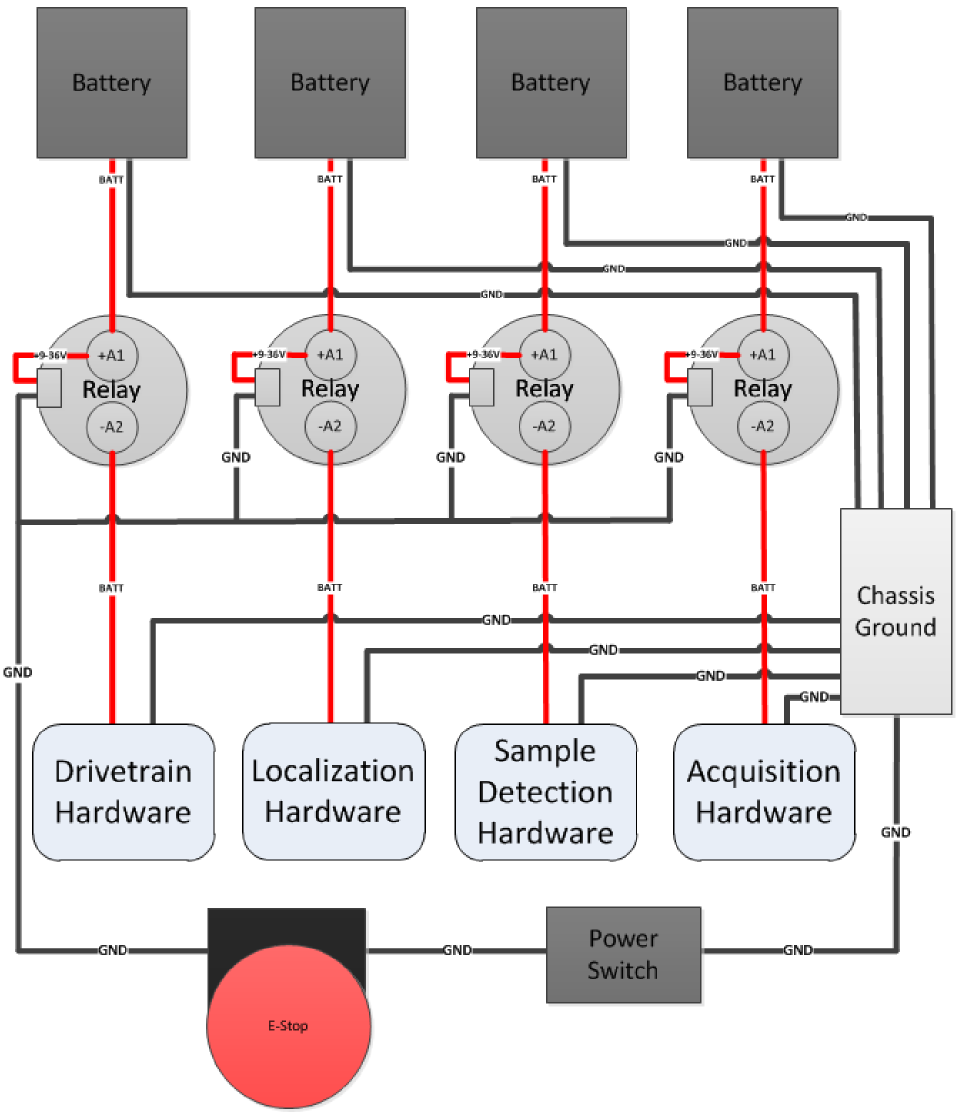

Figure A.1: Emergency Stop Schematic

A.2 Module Schematics

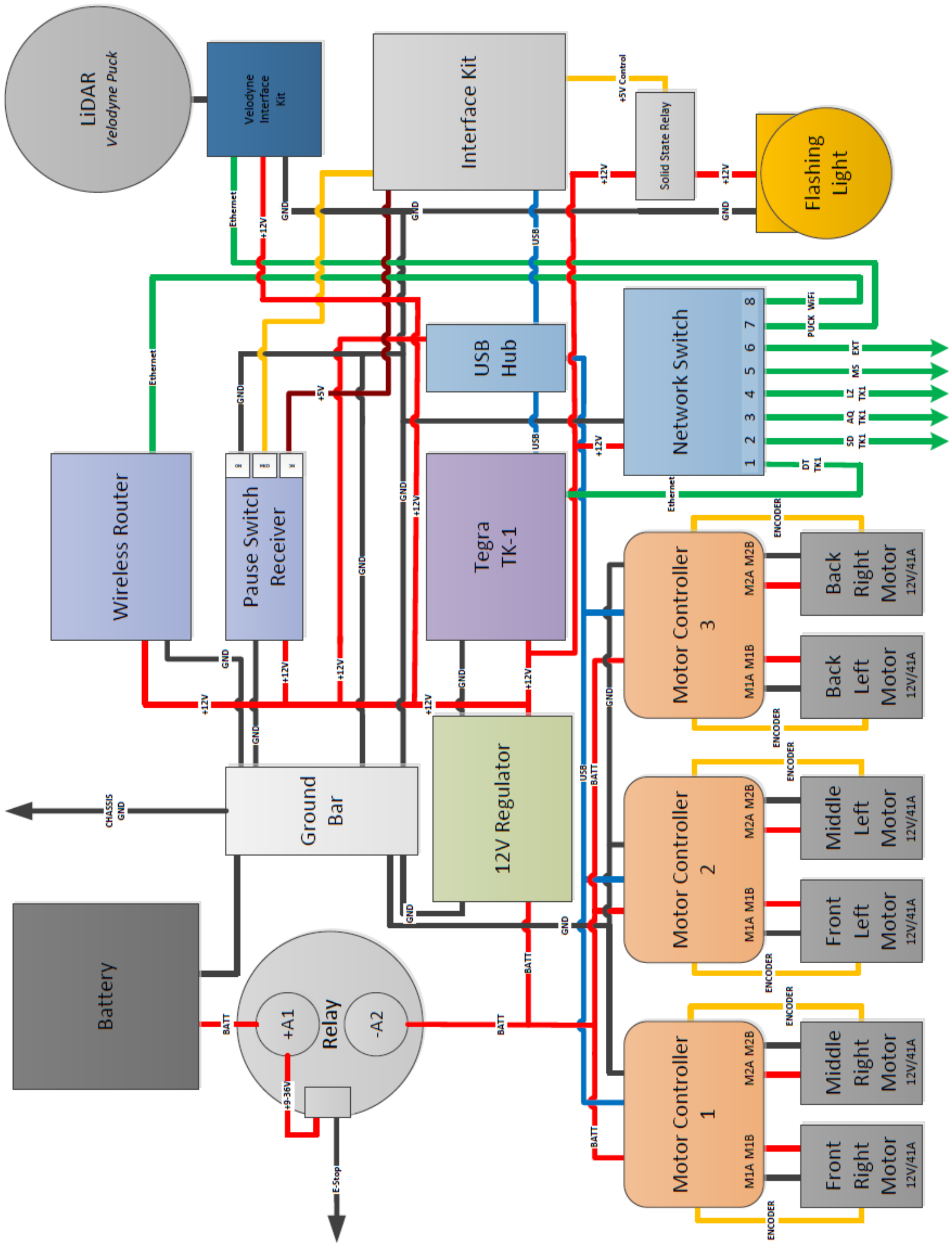

Figure A.2: Drivetrain Electrical Schematic

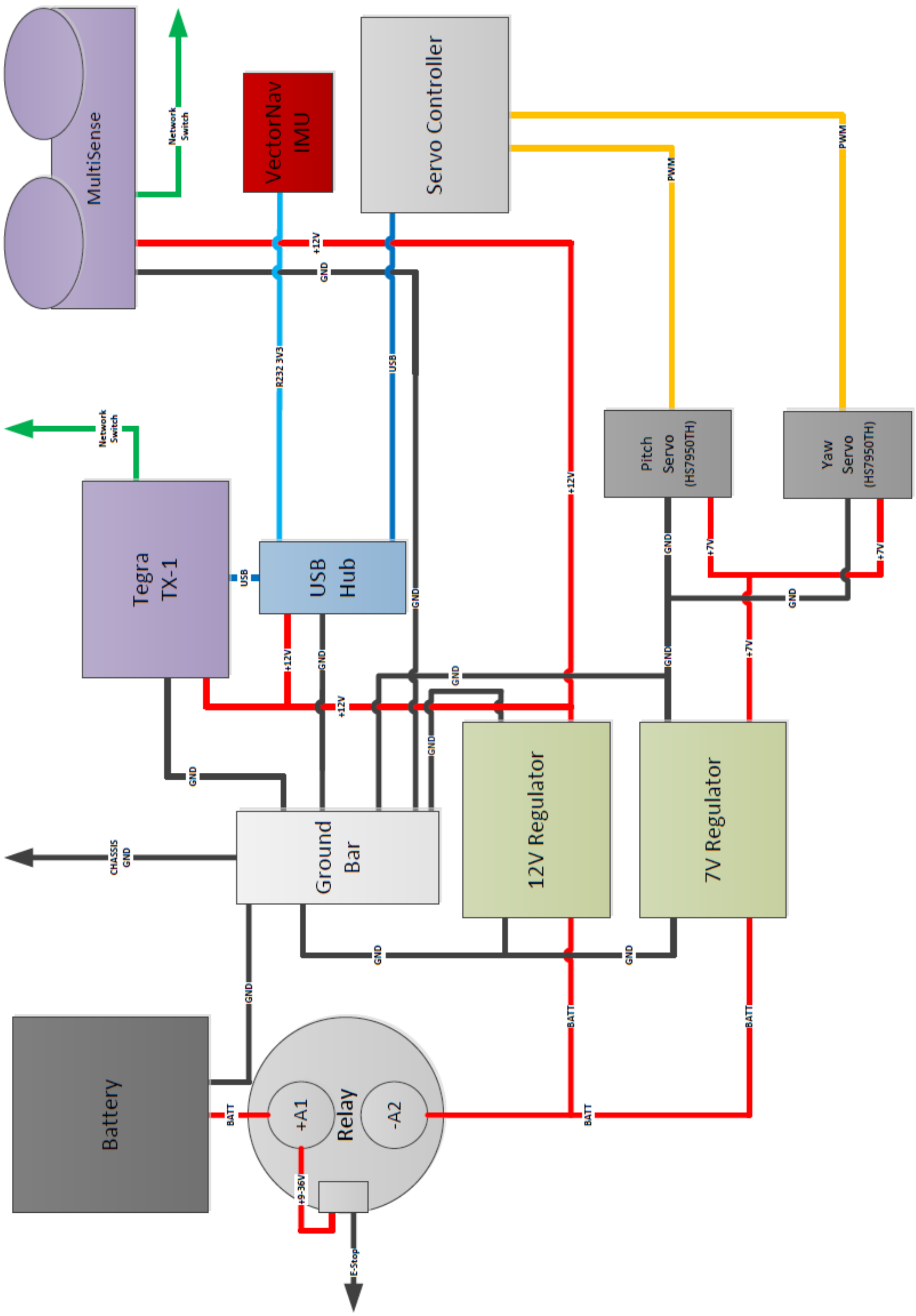

Figure A.3: Localization Electrical Schematic

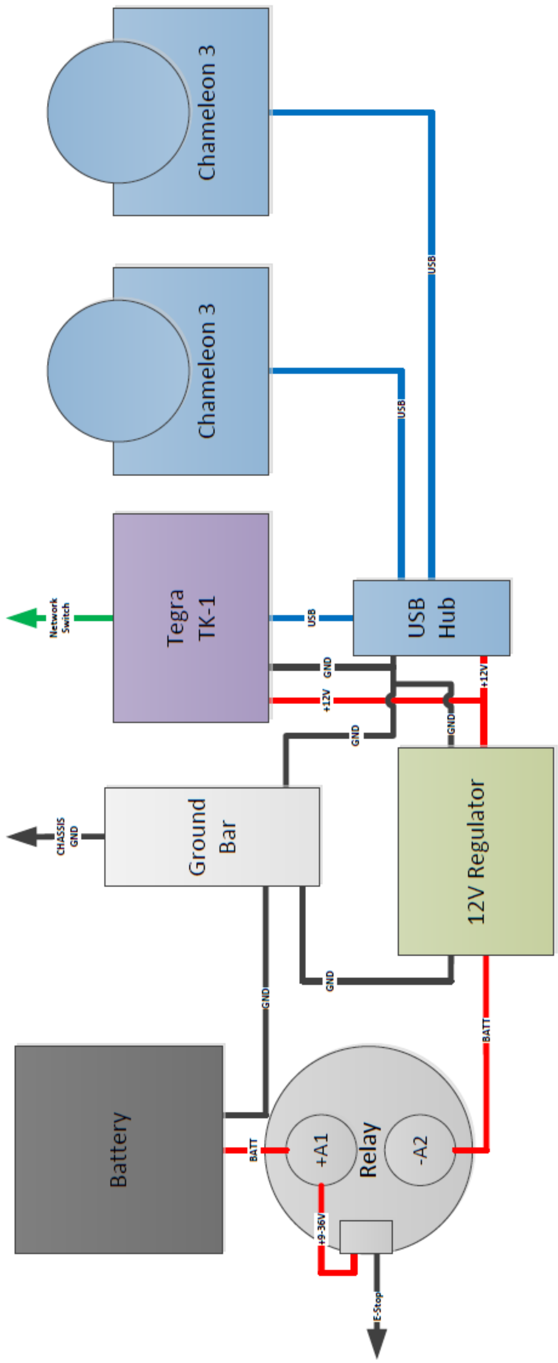

Figure A.4: Sample Detection Electrical Schematic

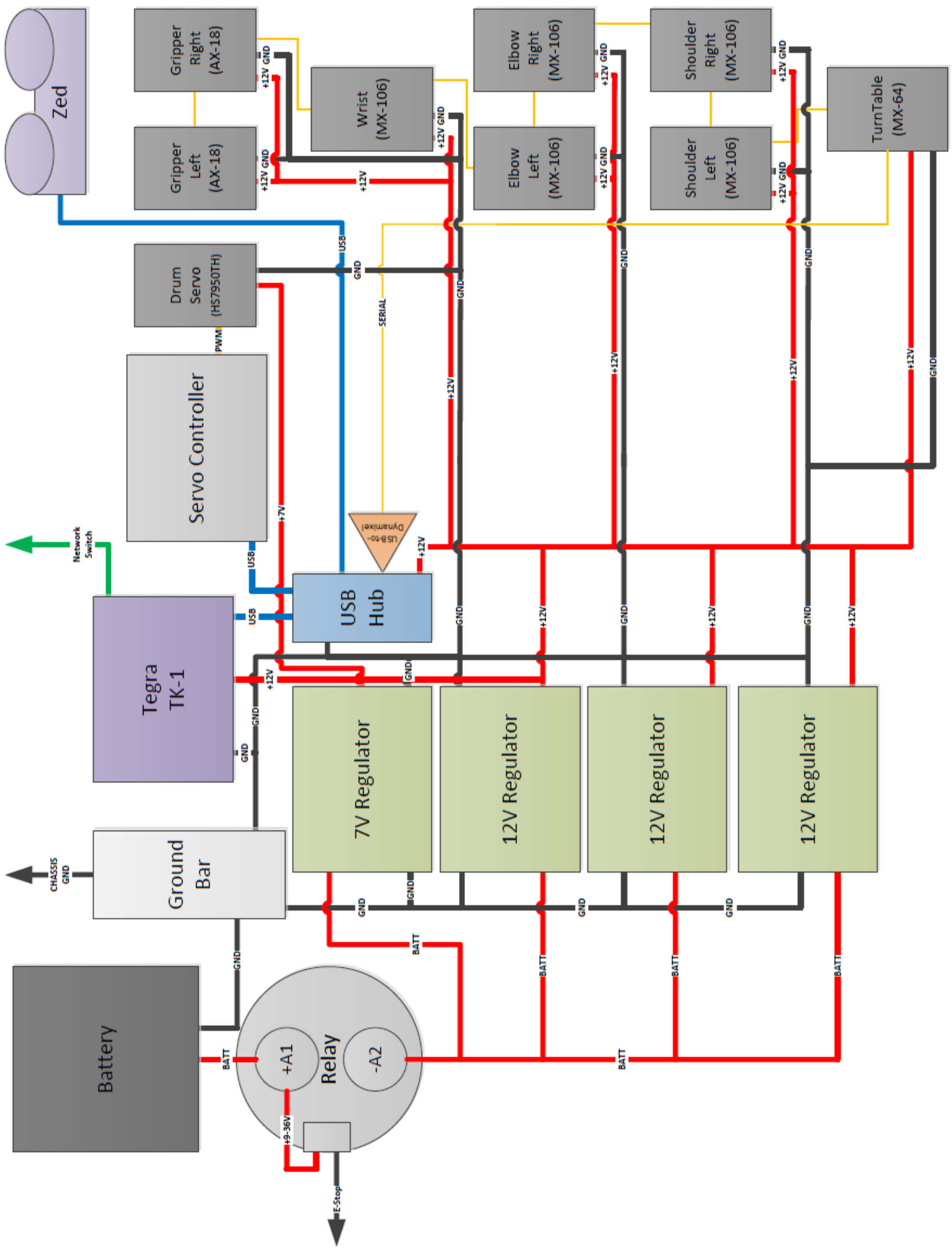

Figure A.5: Acquisition Electrical Schematic

A.3 Encoder Schematic

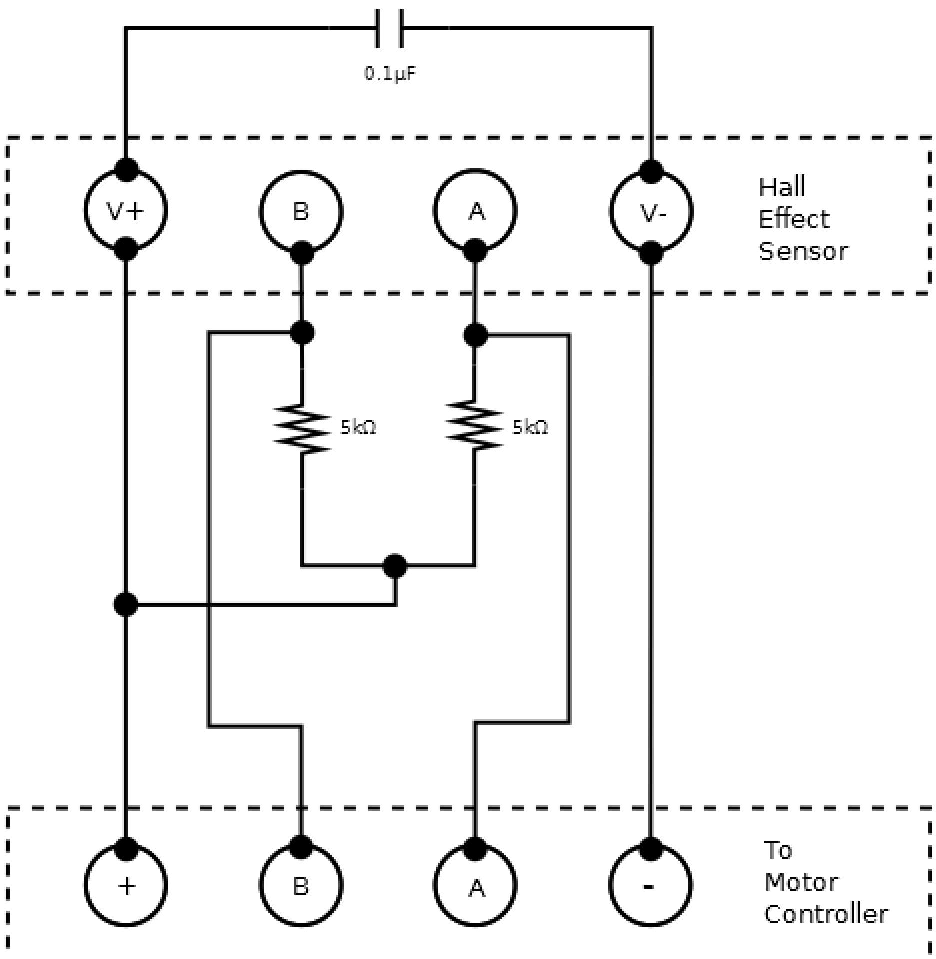

Figure A.6: Encoder Electrical Schematic