University of Colorado, Boulder
Department of Aerospace Engineering Sciences
Senior Projects - ASEN 4018

Articulated Transporter for Local Acquisition and Storage

(ATLAS)

Project Final Report

Monday 4th May, 2020

1. Information

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2. PREAMBLE

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Nomenclature

ATLAS	Articulated Transporter for Localized Acquisition and Storage
MR	Mother Rover
CSR	Child Scout Rover
CSCA	Child Scout Carrying Arm
CD	Child Drone
GS	Ground Station
LOI	Location of Interest
CHIMERA	CHild drone deployment MEchanism Retrieval Apparatus
DRIFT	Drone-Rover Integrated Fire Tracker
HERMES	Hazard Examination and Reconnaissance Messenger for Extended Surveillance
INFERNO	INtegrated Flight Enabled Rove for Natural disaster Observation
MCU	MicroController Unit
MPU	MicroProcessor Unit
EPS	Electrical Power System
COMM	External Communications System
SBC	Single Board Computer

3. Project Purpose

Authors: Emily Weidenfeller, Sage Herrin

3.1. Field of Application

The JPL Fire Tracker System's field of application encompasses better understanding wildfires by recording environmental data in wildfire prone areas, and near wildfires themselves. This will help improve early detection, containment, and characterization methods. There are few other systems, like the JPL Fire Tracker System, that are built to gather information about fires so that their behaviour can be better understood. JPL is currently developing an A.I., AUDREY (Assistant for Understanding Data through Reasoning, Extraction, and Synthesis) and POINTER (Precision Outdoor and Indoor Navigation and Tracking for Emergency Responders)[1][2]. POINTER was created to help track lost firefighters. AUDREY was created to make predictions about what the fire wold do next, and thus recommend the safest course of action to the first responders. The Fire Tracker System is similar to the projects previously mentioned, in that it is designed to help humans better understand fires, and to help keep first responders safe.

The Fire Tracker system is composed of four heritage projects, plus ATLAS, the project sponsored for the 2019-2020 academic year. The four heritage projects are as follows in chronological order: INFERNO, CHIMERA, DRIFT, and HERMES. The INFERNO drone system sought to deploy a remote temperature sensing package 200 m away from a ground station, while recording aerial imagery. It was intended to provide flame front data to personnel in the event of a wildfire. CHIMERA sought to create a landing pad capable of securing and charging the INFERNO drone. DRIFT built upon the two previous efforts, and sought to create a mobile base for the CHIMERA platform. It was designed to travel 500 m across open terrain, and deploy the INFERNO drone via the CHIMERA platform. HERMES was intended to be a path finding child scout rover for the large DRIFT mother rover.

ATLAS' role in the overall Fire Tracker System contributes to the system's overall application of better understanding wildfires.

3.2. Design Problem Addressed

The design problem ATLAS addresses is the fact that the mother rover lacks the capability to deploy, retrieve, and store the child scout rover. ATLAS shall provide the latter capabilities while maintaining the capabilities of all heritage projects.

The two heritage projects that ATLAS will deal with are DRIFT and HERMES. ATLAS will be attached to the mother rover in order to provide the capabilities to deploy, retrieve, and dock the child scout rover, without impeding upon the capabilities of either heritage project. Successfully implementing ATLAS onto the mother rover will allow it to carry the child scout rover a distance from the ground station deployment site. Furthermore, it will allow the child scout rover to be deployed and retrieved, after it has scouted a path for the mother rover. Then the mother rover will take the path that the child scout rover previously scouted. ATLAS will allow the mother rover to safely transport the child scout rover as well as bring it back to the ground station. ATLAS will complete these tasks by receiving ground station commands and send data wirelessly to the ground station, via a human operator. It will also sense the position and orientation of the child scout rover. Lastly, ATLAS will operate in a mission defined forest environment.

3.3. Predicted Benefits

The main benefit of adding ATLAS to pre-existing heritage missions is increased mission efficiency and usability. Adding a carrying mechanism for the child scout rover will allow the child scout rover to be easily transported. Rather than driving along side the mother rover, the child scout rover can be retrieved and carried. This applies to when the mother rover is investigating an area of interest, driving on its own, or returning to the ground station.

Having the child scout rover docked allows improved usability since it requires less people to control both the child scout rover and mother rover simultaneously during these traversal periods. Miscommunications between multiple operators could cause damage to the mother rover or child scout rover, if the two were to collide.

Furthermore, the child scout rover is much easier to keep track of when docked. Additionally, the mother rover may not always need the child scout rover to investigate the path forward, but may need it for other parts of the mission, this is much easier to implement if the child scout rover is docked to the mother rover. This is in comparison to making sure the child scout rover is keeping up with the mother rover, during the mission.

4. Project Objectives and Functional Requirements

Author: Emily Weidenfeller, Miriam Rosenshein, Jamison Bunnell

4.1. Levels of Success

The Levels of Success table, shown in Table 1, detail some of the critical goals of the mission. These elements are broken up into 4 levels, with level 1 representing the minimum measurement of success that ATLAS must meet to be considered successful. Level 4 represents what the team planned to accomplish. There are four criteria, Structure, Control, Communication, and Sensors. The Levels of success explicitly state environmental requirements however a full list of those applied to heritage technology and thus to ATLAS can be found in Table 2.

Table 1: Level of Success

Criteria	Structure	Control	Communication	Sensors
Level 1	Deploy/retrieve the CSR on flat ground.	Control laws move motors in an intended direction.	The ground station communicates with ATLAS while 0 meters away.	Sensors provide one view of the CSR.
Level 2	Deploy/retrieve the CSR on a flat plane and carry the CSR on a flat plane	Control laws move motors, in an intended direction, with a latency less than 1 second.	The ground station communicates 250 meters away from ATLAS with 0 trees per acre.	Sensors provide visual data (100°) of the CSR from two angles (above CSR and from the MR POV)
Level 3	Deploy/retrieve the CSR on a flat plane and carry the CSR on planes between $-20°$ and $+20°$.	Control laws allow for joint station keeping. Controls move motors, in an intended direction, with a latency less than 1 second.	The ground station communicates 250 meters away from ATLAS with 100 trees per acre.	Sensors provide visual data (100°) of the CSR from two angles (above CSR and from the MR POV). Limit switches prevent damage by preventing frames from extending outside their operational zone.
Level 4	Deploy/retrieve the CSR on a flat plane ($\pm 5°$ from the horizon) and carry the CSR on planes between $-20°$ and $+20°$.	Control laws allow for joint station keeping. Control laws move motors, in an intended direction, with a latency less than 300 milliseconds.	The ground station communicates 250 meters away from ATLAS with 170 trees per acre.	Visual camera has 120° with overlaid guidelines to guide the driving of the CSCA. Limit switches prevent damage by preventing frames from extending outside their operational zone.

4.2. Environment Definition

Table 2 describes the environment in which ATLAS will operate in. The environmental definitions seen below are derived from heritage mission environments and the location of Boulder, CO.

Table 2: Heritage Environmental requirements

Environment	Slope	Trees/Foliage	Temperature	Moisture Level
A	0°	Open: 0 trees per acre	41° F	Air: < 37% Soil: < 25%
B	10°	Understocked: 100 trees per acre	41° F	Air: < 37% Soil: < 25%
C	20°	Fully Stocked: 170 trees per acre	41° F	Air: < 37% Soil: < 25%

4.3. Concept of Operations

Below is the CONOPS for all heritage projects. Circled in green is the team's main mission, ATLAS. More specific mission CONOPS are described below.

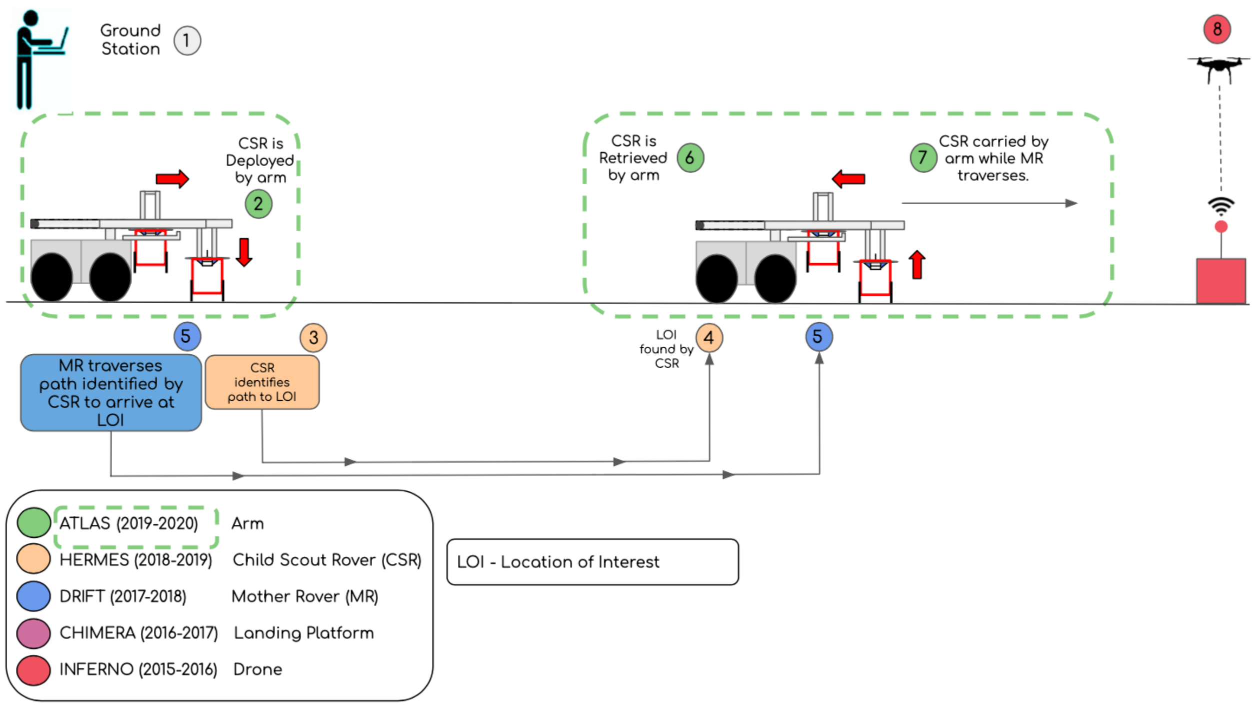

Figure 1: General CONOPS

Below is the CONOPS for ATLAS' mission in relation to the mother rover and the child scout rover mission (DRIFT & HERMES). This is a general overview of ATLAS' mission and does not delve into the specifics. The main phases of ATLAS's mission include deployment and retrieval. HERMES' mission will occur in between the two phases. Note that ATLAS is one-hundred percent operated by a human operator.

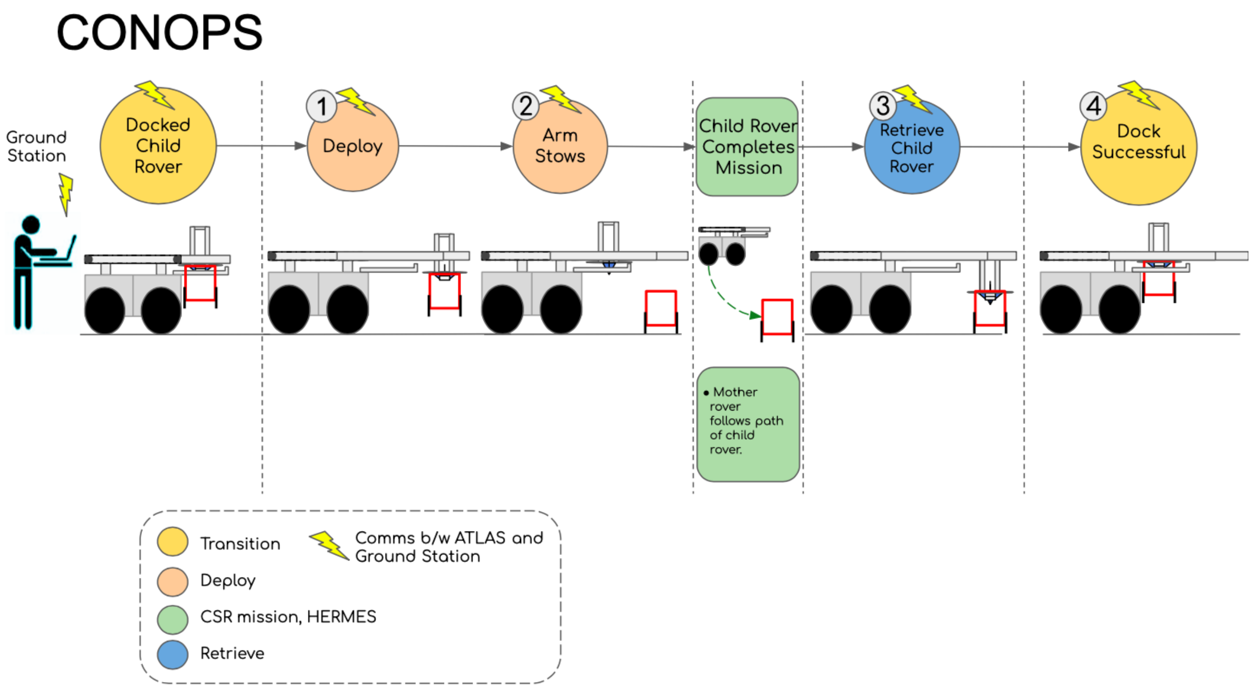

Figure 2: General CONOPS

Below are the order of operations for the deployment and retrieval phases of the mission. This is a more detailed description of how ATLAS performs its mission. The order of operations also includes linked requirements in order to mitigate risks.

Below is the deployment phase of the mission. This starts with the child scout rover in a docked position. Then the human operator will command ATLAS to start the deployment process. The process starts with the extension frame moving outward along with the child scout rover. Then, using live video feed and guidelines, the human operator will command the vertical frame to move downward with the child scout rover. Next, the human operator will confirm that the child scout rover has made contact with the ground using live video and guidelines. Once this has been confirmed, the human operator will command the end effector to un-clasp from the child scout rover interface plate. Lastly, ATLAS will be commanded to return to a stowed position. The word "stowed" in this context is defined as when ATLAS is in a secured position without the child scout rover, and the mother rover is ready to traverse.

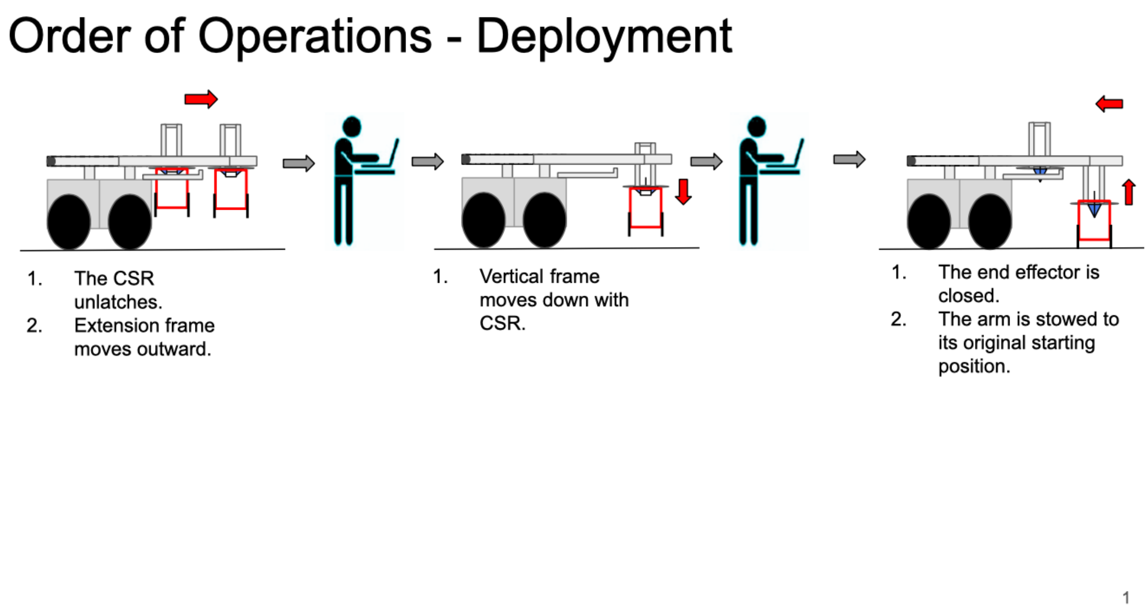

Figure 3: Order of Operations: Deployment

ATLAS has a requirement that is stated in the image below. It is important to address the requirement in the context of operations, because if the requirement is not met, the operations for deployment will be interrupted. ATLAS will be required to stop all operations and the child scout rover will be returned to a docked location. Then the mother rover will traverse to a new location for the next attempt at deployment.

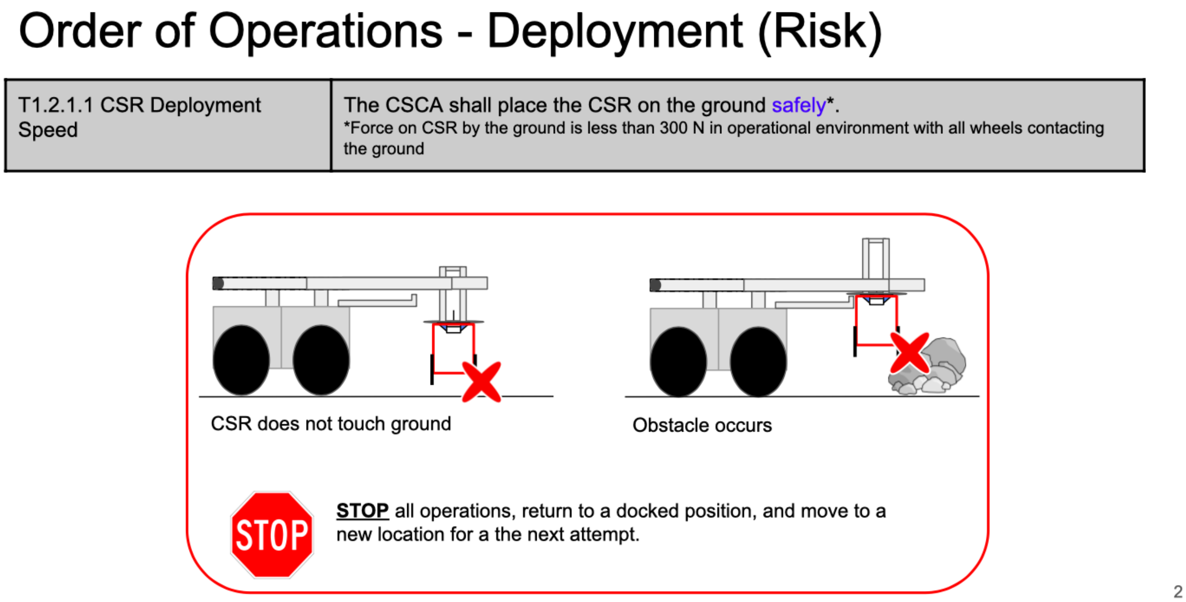

Figure 4: Order of Operations: Deployment Risks

The next phase of the mission is retrieval. Retrieval starts by first making sure the child scout rover is in the operational area. The operational area is defined as when the child scout rover is one meter in front of the mother rover, in an upright position, and on the same plain as the mother rover with a tolerance of $\pm$ 5°. Once this has been confirmed using live video and guidelines, the human operator will command ATLAS to start the retrieval phase. The extension frame will move outward. Then the human operator will confirm that the child scout rover is within sight of the camera located on the end effector, facing downward towards the ground. Then the human operator will use live video and guidelines to actuate the vertical frame downward. The human operator will continue until the end effector is in the child scout rover interface plate, or hole. Then the human operator will confirm that the end effector back plate is making contact with the child scout rover interface via limit switch feedback and live video. After confirmation, the end effector will be commanded to be actuated, and it will clamp onto the child scout rover interface. The human operator will confirm that the end effector is securely clamping onto the child scout rover interface plate via limit switch feedback. The limit switch will be located on the end effector actuating screw. When the limit switch is triggered, the end effector will be fully actuated, and be clamped.

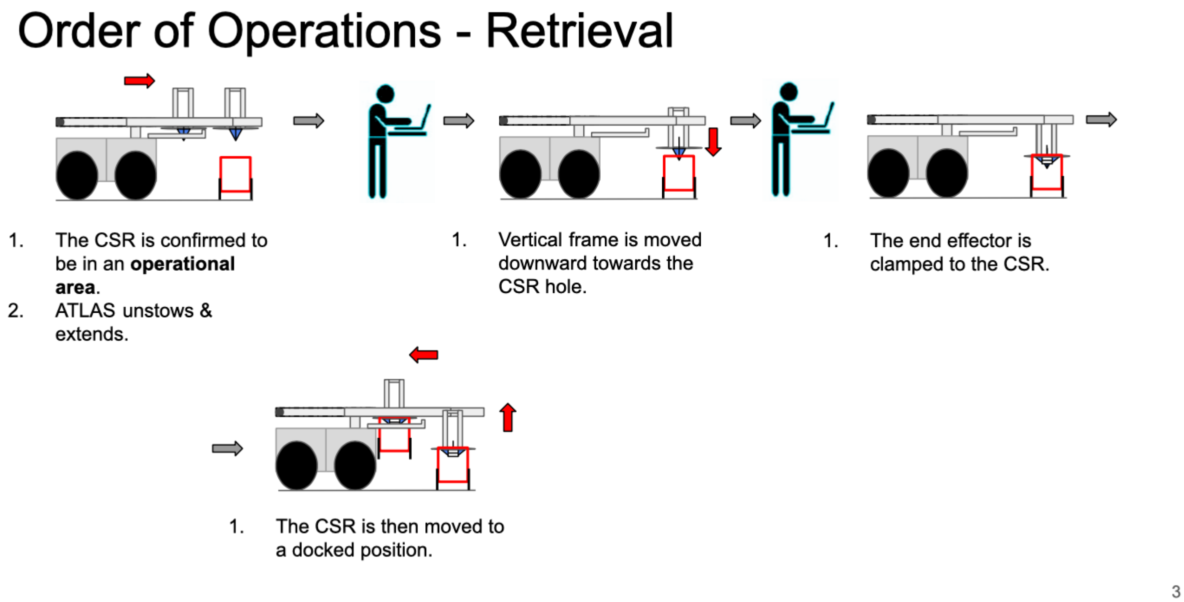

Figure 5: Order of Operations: Retrieval

ATLAS has a requirement that is stated in the image below. It is important to address the requirement in the context of operations, because if the requirement is not met, the operations for retrieval will be interrupted. ATLAS will be required to stop all operations and the arm will be required to be stowed. Then the child scout rover and the mother rover will independently traverse to a new location for the next attempt at retrieval.

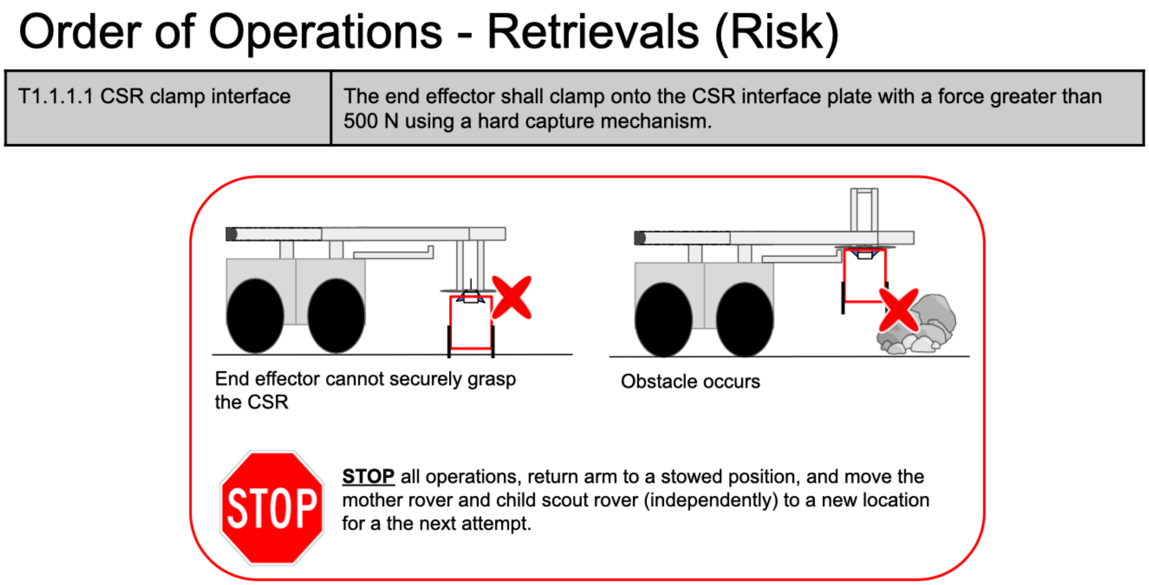

Figure 6: Order of Operations: Retrieval Risks

4.4. Functional Block Diagram

Figure 7 below shows the high level overview functional block diagram for ATLAS. The ATLAS mission starts with the ground station, color coded in red. The human operator, located at point one in a white box, sends string commands through the communication system via keyboard input. ATLAS has its own communication system, separate from heritage projects. The string then arrives at the SBC where it is processed. The sting is then sent to the microcontroller (MCU) where it corresponds to a specific command within the code of the MCU. The MCU then controls the motors and motor drivers. These then actuate the arm and end effector, which then physically interact with the child scout rover.

The human operator decides what commands are sent and when. In order for the human operator to perform the commands in real time and control ATLAS, they must receive position feedback for the arm, end effector, and child scout rover. ATLAS will provide the position feedback in the form of two live video feeds and multiple limit switches. The limit switches are placed on the extreme points of the arm, as well as parts of the end effector. The limit switch feedback will be received by the MCU, sent to the SBC where it is processed, and then sent back over the communication system to the ground station. The live video feed will be sent straight to the SBC in the form of a USB input, where it will also be processed and sent back to the ground station. Then the human operator will use the position feedback to make a decision regarding the next command. The process will then repeat.

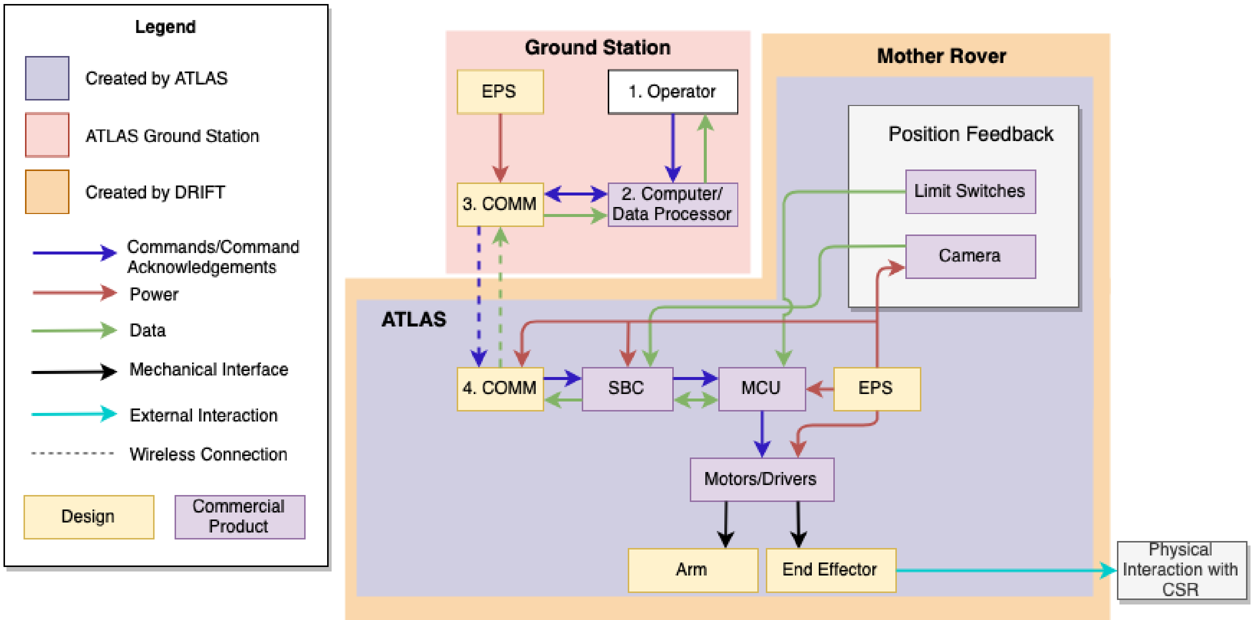

Figure 7: Functional Block Diagram: High Level Overview

4.5. Functional Requirements

Functional requirements define the team's contract with the customer and drive the trade studies for ATLAS. Presented here are the functional requirements from which all design requirements flow down from. For the functional requirements, any "T" means "technical". On the other hand, any "L" stands for "logistical" and is related to heritage projects interacting with ATLAS.

T1.1 CSCA to CSR Mechanical Interface: The CSCA shall carry the CSR.

Motivation: It is a project requirement to deploy, retrieve, and dock the CSR. ATLAS must have the ability to interface with the CSR. Also. the CSR must remain in storage when the MR is moving so that it can be deployed.
Means of Verification: Inspection - The team will visually verify that the CSCA has interfaced with the CSR. Also, if all children requirements underneath this requirement are verified, then the functional requirement will be verified.

T1.2 Deploy the CSR: The CSCA shall deploy the CSR.

Motivation: Deployment is defined as undocking the CSR from the CSCA and setting it down on terrain. This is necessary for the CSR to complete its mission of scouting a path for the MR.
Means of Verification: Test - The team will conduct multiple tests in relation to the children requirements. If all children requirements underneath this requirement are verified, then the functional requirement will be verified.

T1.3 Retrieving the CSR: The CSCA shall retrieve the CSR when it is in operational position.

Motivation: Retrieval is necessary for the re-use of the CSR in future missions. Re-interfacing is vital to retrieval. Operational position is defined as when the CSR is within the one meter by one meter square in front of the MR and is upright.
Means of Verification: Test- If all children requirements to this requirement are verified then functional requirement will be verified as well.

T1.4 CSCA to MR Mechanical Interface: ATLAS shall remain physically attached to the MR during mission operations

Motivation: A solid connection to the MR is necessary when the CSCA is experiencing loads. The CSCA needs to be attached to the MR to complete its mission. Shear force analysis should be done on this interface.
Means of Verification: Test- The team will conduct tests on the CSCA to MR interface to ensure that it will remain attached while undergoing operational conditions.

T2.1 Control of the CSCA: ATLAS shall have a sensor subsystem for guidance of the CSCA.

Motivation: This is to help guide the human operator in commanding ATLAS.
Means of Verification: Test - The team will ensure the chosen camera will provide visual data.

T2.2 Avoidance of Damage: ATLAS shall have sensing to ensure ATLAS stays in the operational zone.

Motivation: This requirement is presented to prevent damage of heritage and current projects. It is also in order to help guide the human operator when commanding ATLAS.
Means of Verification: Test - The team will ensure the chosen sensor provide accurate measurements by performing preliminary tests.

T3.1 Remote Control: ATLAS shall perform commands that are received from the GS.

Motivation: ATLAS requires commands from an operator for different phases of the mission. The operator will be located at the ground station.
Means of Verification: Test - The team will ensure ATLAS will execute commands sent by the GS by sending test commands.

T3.2 Data Handling: ATLAS shall handle sensor data

Motivation: Sensor data needs to be displayed in a way that is understood by a human operator at the GS.
Means of verification: Test - If all children requirements to the functional requirement, T3.2, are verified, the data handling requirement will be verified.

T4.1 ATLAS Two Way Communication: AtLAS shall engage in two way wireless radio communication with the GS

Motivation: There must be two way communication to send information about the state of ATLAS to the GS and also to send commands from the GS to ATLAS.
Means of Verification: Test - If all children requirements underneath this requirement are verified, then the functional requirement will be verified.

T5.1 ATLAS Power: ATLAS' power subsystem shall provide power to other subsystems.

Motivation: ATLAS will not function without power.
Means of Verification: Analysis - If all children requirements underneath this requirement are verified, then the functional requirement will be verified.

L1.1 HERMES Capabilities: ATLAS shall allow HERMES' systems to remain the same by only modifying the top plate of the CSR

Motivation: HERMES original systems will be untouched to ensure it may complete its mission. The only change is the removal of a non-mission critical cover. A weight bearing frame will be implemented in its place.
Means of Verification: Analysis - The team will perform analysis/inspection on each component of HERMES that ATLAS interacts with.

L1.2 DRIFT Capabilities: ATLAS shall allow DRIFT's systems to remain the same by staying away from DRIFT systems.

Motivation: The capabilities of DRIFT must be maintained while completing ATLAS mission objectives in order for the full Fire Tracker system to operate as a cohesive unit. This applies to all phases of the mission.
Means of Verification: Analysis - The team will perform analysis/inspection on each component of DRIFT that ATLAS interacts with.

L1.3 CHIMERA Capabilities: ATLAS shall allow CHIMERA systems to remain the same by staying outside of the zone of CHIMERA operation.

Motivation: The capabilities of CHIMERA must be maintained while completing ATLAS mission objectives in order for the full Fire Tracker system to operate as a cohesive unit. Staying out of the zone of CHIMERA will allow it to complete its mission.
Means of Verification: The CHIMERA operational zone will be defined and CAD will be used to verify that ATLAS stays outside the defined zone.

4.6. Project Deliverables To The Course and Customer

The following project deliverables were sent to the customer and delivered to the PAB members.

- Preliminary Design Document (PDD)
- Critical Design Document (CDD)
- Preliminary Design Review (PDR)
- Critical Deisgn Review (CDR)

Not listed are weekly status reports, sent to both the customer and advisor, as well as weekly time sheets. Regarding the list above, the PDD was a high level overview of the project. The document helped the team become familiar with the project and defined the mission's objectives and levels of success. The PDD also included the team's first draft of the CONOPS and functional block diagram. The CDD mainly consisted of trade studies that the team performed in order to come to a conclusion regarding the baseline design. The document was an important step in the design process. This is when design choices were starting to be made. The PDR was a presentation that was presented to the customer and PAB members. In summary, the PDR was a presentation form of the CDR, however it included preliminary analyses regarding the team's design choices. The team was required to review their design choices and determine whether or not they were feasible. The team also had to learn how to prove that their design was feasible to someone else. Lastly, the CDR was a very detailed presentation of the designing of ATLAS. "Very detailed" refers to knowing the design of ATLAS down to the bolt. The presentation's purpose was to prove to the PAB and customer that the design of ATLAS was feasible and would be functional once built.

5. Design Process and Outcome

Authors: Clara Bader, Colton Kalbacher, Ender Kerr, Charles MacCraiger, Wyatt George, Kelan Crespin, Miriam Rosenshein, Pierce Costello, Jamison Bunnell, Jason Leng, Emily Weidenfeller, Sage Herrin

5.1. Conceptual Design

5.1.1. Hardware

a. CSCA Kinematics The 'carrying-arm' aspect of ATLAS was one of the most critical components of the project, as it determined how the system would maneuver in order to dock, deploy, and retrieve the CSR. Each design considered had a unique work envelope. This refers to the size and shape of the work space in which the system could operate. The complexity and flexibility of the system were ultimately determined by the arm design, so choosing the right method was critical for fulfilling the requirements of the project. The functional requirements associated with the CSCA Kinematics section were such that the CSCA needed to obtain the capability of lifting and carrying the child scout rover.

The design options considered were the virtual four bar articulated arm, cylindrical, and the Cartesian gantry crane. Each option would enable the CSCA to effectively retrieve, deploy, and carry the Child Scout Rover. Each of these options were evaluated in the Trade Studies section of the Fall Final Report in order to enable the team to select the most viable option. Characteristics considered included the weight of the design, the development time, the "strength" of the design, the cost of the design, and the power draw. Additionally the likelihood that the design would cause the mother rover to tip over was considered, as well as how much the design added to the mother rover footprint. The Mother Rover was already very large, and adding more weight to it would only impede its traversal ability.

b. End Effector The end effector conceptual designs considered included the forklift, hard-capture mechanism, the traditional latching mechanism, and the mechanical gripper. Trade studies were conducted to compare these various designs with each other, as well as to assess each design's ability to achieve functional requirements. Metrics for these trade studies included: weight, cost, development time, strength, and power draw.

c. Trade Study Results Trade study metrics for both the CSCA kinematic and end effector designs included: strength, weight, development time, power, maneuverability, and cost.

The "Cartesian Gantry Crane" received the highest score by a significant margin. This design is strong, and doesn't significantly add to the footprint of the mother rover. The three degrees of freedom it offers allowed for enough maneuverability to retrieve the Child Scout Rover in a variety of terrain settings.

The baseline design recommended for the end effector was the "Hard Capture Mechanism". It performed average or better in all categories. This is why it was able to achieve the highest score and was thus the team's baseline recommendation. This mechanism is inspired by the current docking system used by crewed spacecraft visiting the International Space Station. In addition to having the highest trade study score, the hard capture mechanism was chosen because it enables a secure capture mechanism while allowing for flexibility in alignment.

5.1.2. Electronics

a. Control and Data Handling The options for micro-controllers and microprocessors were plentiful. For the purpose of this study, the goal was to limit the design pathways for the processing system in order to narrow the design scope. There existed the option to design a custom micro-processing/controller board using the AERO building's fabrication facilities. However, the main benefit of a custom board was the ability to tailor the weight and size of the system to specific requirements. The drawbacks to custom boards were a vastly increased development time and increased complexity. The custom board design path was also strongly discouraged by Trudy Schwartz as the benefits of such a design were not tantamount to this project's constraints. As the ATLAS project was not necessarily limited to weight and sizing constraints, this option was discarded upon initial review. The remaining design pathways were mostly restricted by the optical sensor, wireless video transmission, the number of actionable joint motors/servos, and the necessary sensor array attached to measure the state of the CSCA. These restrictions placed lower limits on the processing speed and the required number of input/output pins accessible on the chosen controller.

In general, the control and data handling system designs considered included: having a dedicated video processing on MPU with Separate MCU, having a separate MCU for each subsystem, and having one MCU on ATLAS with the image processing on the GS.

b. Video Camera Video camera options considered included first person view (FPV) drone cameras, USB cameras, and GoPros. All of the options considered were able to be used either with the point to point network, a micro-controller, or microcomputer. The video camera trade study used the following metrics: cost, integration, and latency.

c. Communication Communication between the GS and ATLAS was a critical component for the ATLAS project. The GS needed to be able to send commands to ATLAS, and ATLAS needed to be able to send data and live video back to the GS. The communication system selected certain criteria and restrictions such as: range, environmental attenuation, data rate, and existing system interference. The maximum range that the commands and data would be sent over during a mission is 250 meters. This communication needed to be carried out in the mission environments previously stated. These environments contain trees and other obstacles that can obstruct the signal. Commands and data must still be able to transmit if direct line of sight is not possible. Studies found showed that higher frequencies are attenuated more while passing through forests, so lower communication frequencies are generally preferred. It was determined that the communication system required a data rate between 10-15 Mbps so that live video could be transmitted with enough resolution that the CSCA could be controlled by a human operator. The communication systems of previous projects were also taken into account to avoid interference with the heritage systems. The selected system met all these criteria well. Antenna size for each concept was assumed to be the same. The overall considered design options were a Point to Point Network, RF Transmitter/Receiver Modules, and Cellular Data Connection.

d. Trade Study Results The results of the latter three trades led the team to use a dedicated MCU and a single SBC for video transmission. A USB camera was determined to be the best choice to work with ATLAS's point to point network, and the decision was influenced by HERMES camera choice as well. The Point to Point Network was chosen as the best communication system.

5.1.3. Software

a. Programming Language Software was one of the core design elements of ATLAS, due to the nature of the project. It also depended on the level of human interaction chosen by the team. The level of human interaction was eventually chosen to be a high level. This influenced the final decisions with regards to the programming language used.

The programming languages considered were Python, Java, Matalab & Simulink, C++, and C. The metrics used to perform the trade study were the speed/run time, prior knowledge, external resources (such as tutorials) compatibility , and readability/ease of use).

b. Trade Study Results The results of the trade study demonstrated that Matlab & Simulink, C++, and Python all came out on top. It was decided that Matlab would be used or simulations and analysis in regards to testing specific requirements and preliminary testing or calculations. Python, along with the SBC and MCU, was used for designing the graphical user interface for the human operator.

5.2. Requirements Flow-Down

]**Authors:**Miriam Rosenshein, Emily Weidenfeller, Clara Bader, Kelan Crespin, Wyatt George, Charles MacCraiger

The following section shows how functional requirements lead to detailed design requirements. Note that "T" requirements are Technical, while "L" requirements are Logistical, usually related to heritage projects. The team uses a numbering system in regards to how the parent requirements are linked to the child requirements. Functional requirements only include two numbers after a "T" or "L". Anything more than that is a design requirement, which will have a corresponding parent requirement. The following section of the report will be organized by functional requirement.

5.2.1. T1.1 CSCA to CSR Mechanical Interface

T1.1 CSCA to CSR Mechanical Interface: The CSCA shall carry the CSR

Motivation: The CSR must remain in storage when the MR is moving so that it can be deployed
Means of Verification: Inspection - If all children requirements to this requirement are verified, the CSR carry requirement is verified
Assessment: Testable, Clear

T1.1.1 CSR Dropping: The end effector shall grip the CSR during transportation

Motivation: If the CSR is dropped the mission will fail.
Means of Verification: Test - The children requirements of this requirement ensure the clamp is strong enough to sustain the weight of the CSR and that it will not be shaken loose. If both of those are verified this is also verified.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because if ATLAS cannot grip the CSR ATLAS will also be unable to carry the CSR.
Assessment: Testable, Define ”grip” more succinctly

T1.1.1.1 CSR Clamp Interface: The end effector shall clamp onto the CSR interface plate with a force greater than 300 N using a hard capture mechanism.

Motivation: Test - The end effector will strongly clamp onto the CSR interface plate to ensure no slipping or dropping at any point of the mission.
Means of Verification: Test - The team will measure the force applied by the hard capture mechanism onto a plate using a pressure sensor.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because if the grip on the CSR

is too weak ATLAS will be unable to carry it over rough terrain.
Assessment: Testable, Clear

T1.1.1.2 CSR Vibration During Transport: The CSR shall oscillate with an angular velocity less than 1 rad/s during transportation on the MR.
Motivation: The CSR or the CSCA may sustain damage is there is too much vibration while the MR is moving. This number was chosen as acceptable because it is a factor of 2.5 away from the excitation vibration of the system.
Means of Verification: Test - The team will utilize vibration machines at CU. The CSCA will be interfaced to a test stand to mimic the interface of the CSCA to the MR. A large mass mimicking the CSR will be held by the end effector and oscillation will be measured at several points along the CSCA.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because if vibration becomes too much ATLAS will be unable to carry the CSR.
Assessment: Testable, Clear

T1.1.1.3 Pin Failure: The pins of the end effector shall experience shear forces less than 55,000 psi (alloy steel).
Motivation: Forces greater than this will cause shear failure.
Means of Verification: Test - Use pressure sensor to see forces at pins.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because if the pins fail the mission will be unable to continue.
Assessment: Testable, Clear

T1.1.1.4 Interface Plate Bending: The interface plate shall bend less than 0.04" while being carried.
Motivation: To reduce danger of breaking/swinging.
Means of Verification: Test - Apply upwards force in middle of plate and downwards force at edges.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because the value given is less than the material failure plus a factor of safety. If the interface plate fails ATLAS will be unable to carry the CSR.
Assessment: Not Testable, Clear

T1.1.2 Up a Slope: ATLAS shall carry the CSR up a slope equal to or less than 20°.
Motivation: DRIFT can traverse up a 20° slope so if ATLAS cannot carry the CSR up/down the same slope the mission will fail.
Means of Verification: Test - The team will either drive the mother rover up a slope while carrying the CSR or create a test fixture (such as a block on a wagon) that can be dragged up a slope to mimic traversal of a hill.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because this is a terrain requirement of heritage technology. If ATLAS cannot carry the CSR on terrain the mission is expected to take place on the mission will be failed.
Assessment: Testable, Clear

T1.1.3 Flat Ground: ATLAS shall carry the CSR over flat ground.
Motivation: DRIFT can traverse flat ground so if ATLAS cannot carry the CSR on flat ground the mission will fail.
Means of Verification: Test - The team will either drive the mother rover on flat ground while carrying the CSR or create a test fixture (such as a block on a wagon) that can be dragged on flat ground to mimic traversal of a hill.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because this is a terrain requirement of heritage technology. If ATLAS cannot carry the CSR on terrain the mission is expected to take place on the mission will be failed.
Assessment: Testable, Clear

T1.1.4 Down a Slope: ATLAS shall carry the CSR down a slope equal to or less than 20°.
Motivation: DRIFT can traverse up a 20° slope so if ATLAS cannot carry the CSR up/down the same slope the mission will fail.
Means of Verification: Test - The team will either drive the mother rover down a slope while carrying the CSR or create a test fixture (such as a block on a wagon) that can be dragged down a slope to mimic traversal of a hill.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because this is a terrain requirement of heritage technology. If ATLAS cannot carry the CSR on terrain the mission is expected to take place on the mission will be failed.
Assessment: Testable, Clear

T1.1.5 Damage the CSR: The CSR shall be docked parallel to the MR.
Motivation: The CSR is most secure when the long end of the CSR is parallel to the MR. Docked is defined in our definitions sheet as a height that allows translation of the MR but also does not obstruct the CHIMERA

landing pad movement.
Means of Verification: Test - The team will dock parallel to the MR.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because if the CSR is docked incorrectly the team cannot move forward knowing no damage will come to the CSR or other heritage technology. Always docking in this position guarantees an expected outcome.
Assessment: Testable, Clear

5.2.2. T1.2 Deploy the CSR

T1.2 Deploy the CSR: The CSCA shall deploy the CSR.
Motivation: Deployment is defined as undocking the CSR from the CSCA and setting it down on terrain. This is necessary for the CSR to complete its mission of scouting a path for the MR.
Means of Verification: Test - If all children requirements to this requirement are verified, the CSR will be deployed.
Assessment: Testable, Clear

T1.2.1 Undocking the CSR: The CSCA shall undock the CSR.
Motivation: Un-docking is the last step of deployment.
Means of Verification: Inspection - Successful docking means the end effector has unclamped from the CSR and is no longer in its path of motion. The team can visually verify this. This can also be verified via limit switch statuses.
Logic: This requirement makes sense as a design choice and as a child of T1.2 because if the CSR is not properly undocked the team cannot guarantee that no damage has been done to any heritage technology.
Assessment: Testable, Clear

T1.2.1.1 CSR deployment speed: The CSCA shall place the CSR of the ground safely.
Motivation: The CSR should be placed on the ground slowly enough that it does not sustain damage.
Means of Verification: Test - An accelerometer will be used to measure acceleration at the tip of the end effector.
Logic: This requirement makes sense as a design choice and as a child of T1.2 because is the CSR is placed down with too great a speed damage may occur to it or to ATLAS.
Assessment: Not Testable, Clear

5.2.3. T1.3 Retrieving the CSR

T1.3 Retrieving the CSR: The CSCA shall retrieve the CSR when it is in operational position.
Motivation: Retrieval is necessary for the re-use of the CSR in future missions. Re-interfacing is vital to retrieval. Operational position is the CSR is within the one meter by one meter square in front of the MR and is upright.
Means of Verification: Test - If all children requirements to this requirement are verified, the CSR will be retrieved.
Assessment: Testable, Clear

T1.3.1 Docking the CSR: The CSCA shall dock the CSR.
Motivation: Docking is necessary to transport the CSR.
Means of Verification: Test - If all children requirements are verified this is fully verified.
Logic: This requirement makes sense as a design choice and as a child of T1.3 because if the CSR is not docked it cannot be retrieved.
Assessment: Testable, Clear

T1.3.1.1 CSCA Tip Deflection: The CSCA shall have a tip deflection less than 0.25” at one meter while lifting the weight of the CSR.
Motivation: If tip deflection is too large belts may become misaligned, heritage technology may sustain damage, and the mission may fail.
Means of Verification: Test - The team will lift the mass of the CSR and end effector at a distance of one meter and measure deflection at multiple points along the CSCA.
Logic: This requirement makes sense as a design choice and as a child of T1.3 because if tip deflection of the extension frame is too large it will cause mechanical failure of the dynamic systems, as well as having the potential for material failure and thus dropping of the CSR.
Assessment: Testable, Clear

T1.3.1.2 Lifting the CSR: The CSCA shall be able to lift the wheels of the CSR at least 6” above the ground.
Motivation: Lifting the CSR is integral to both the deploy, retrieve, and docking phases of the mission. This height has been selected because it does not interfere with the movement of the MR.
Means of Verification: Test - The team will conduct tests where the CSCA will lift the CSR plus the end

effector to the height specified.
Logic: This requirement makes sense as a design choice and as a child of T1.3 because if ATLAS is unable to lift the CSR it cannot retrieve it.
Assessment: Testable, Clear

T1.3.2 Lifting the CSR: The CSCA shall be able to retrieve the CSR when they are both on the same plane (0° +/- 5°)
Motivation: Customer did not specify plane of retrieval. This situation is realistic due to the high functionality of the CSR and its ability to move to a convenient plane of retrieval.
Means of Verification: Test - Use a level to check the CSCA can retrieve that CSR at +/- 5°.
Logic: This requirement makes sense as a design choice and as a child of T1.3 because if ATLAS is unable to lift the CSR it cannot reliably retrieve it from the plane of operation used by heritage technology.
Assessment: Testable, Clear

5.2.4. T1.4 CSCA to MR Mechanical Interface

T1.4 CSCA to MR Mechanical Interface: ATLAS shall remain physically attached to the MR during mission operations.
Motivation: A solid connection to the MR is necessary when the CSCA is experiencing loads. The CSCA needs to be attached to the MR to complete its mission.
Means of Verification: Test - The team will conduct tests on the CSCA to MR interface to ensure that it will remain attached while undergoing operational conditions.
Assessment: Testable, Clear

T1.4.1 CSCA Vibration During Transport: The CSCA/CSR system shall not oscillate with an angular velocity greater than 1 rad/s during transportation on the MR.
Motivation: The CSR or the CSCA may sustain damage if there is too much vibration while the MR is moving. This number was chosen as acceptable because it is below the excitation frequency calculated for the Mother Rover which will reduce the vibrations through the Mother Rover interface.
Means of Verification: Test - The team will utilize vibration machines at CU. The CSCA will be interfaced to a test stand to mimic the interface of the CSCA to the MR. A large mass mimicking the CSR will be held by the end effector and oscillation will be measured at several points along the CSCA.
Logic: This requirement makes sense as a design choice and as a child of T1.1 because if vibration becomes too much ATLAS will be unable to carry the CSR.
Assessment: Test may need a redesign depending on the availability of a vibration machine, Clear

5.2.5. T2.1 Control of the CSCA

T2.1 Control of the CSCA: ATLAS shall have a sensor subsystem for guidance of the CSCA.
Motivation: This is to help guide the human operator in commanding ATLAS.
Means of Verification: Test - The team will ensure the chosen camera will provide visual data .
Assessment: Testable, Binary test only

T2.1.1 CSCA Visual Data: The ATLAS sensor subsystem shall provide visual data of the CSCA with a horizontal angular FOV greater than or equal to 100°.
Motivation: This is to ensure the human operator completes the mission without damage to heritage projects. It is also to ensure the human operator can see the CSCA as well as the surrounding area (functional range).
Means of Verification: Test - The team will ensure the camera placement provides a FOV greater than or equal to 100°.
Logic: The child requirement makes sense since it will help with the deployment and retrieval phases of the mission. Visual data is one of the first things needed when a human operator is involved with a system.
Assessment: Testable, Clear

T2.1.2 CSR Visual Data FOV: The ATLAS sensor subsystem shall provide visual data of the CSR with a FOV greater than or equal to 100°.
Motivation: It is necessary for guiding the human operator to command the CSR. It is also to ensure the human operator can see the CSCA as well as the surrounding area (functional range).
Means of Verification: Test - The team will ensure the camera placement provides a FOV greater than or equal to 100°.
Logic: The child requirement makes sense since it will help with the deployment and retrieval phases of the mission. Visual data is one of the first things needed when a human operator is involved with a system. The FOV has to be large enough to provide an effective view for the human operator.
Assessment: Testable, Clear

T2.1.3 CSR Visual Data Resolution: The ATLAS sensor subsystem shall provide visual data of the CSR with a resolution of 720p.

Motivation: It is necessary for guiding the human operator to command the CSR. 720p corresponds to 16:9 ratio which gives us the full provided FOV by the camera.
Means of Verification: Test - The team will check the output resolution of the visual data is 720p.
Logic: The child requirement makes sense since it will help with the deployment and retrieval phases of the mission. Visual data is one of the first things needed when a human operator is involved with a system. The resolution has to be clear enough for the human operator to command ATLAS.
Assessment: Testable, Clear

T2.1.4 CSR Visual Data FPS: The ATLAS sensor subsystem shall provide visual data of the CSR at a rate of 20 fps or greater.

Motivation: The human operator needs to see commands happen in real time, so future commands can be made. 24 fps is what most movies are shot at. Below 20 isn't desirable. We want the best quality, while not being excessive, for the human operator.
Means of Verification: Test - The team will check the output frames per second of the visual data is 25 fps.
Logic: The child requirement makes sense since it will help with the deployment and retrieval phases of the mission. Visual data is one of the first things needed when a human operator is involved with a system. The frames per second need to be fast enough so the human operator can command ATLAS in real time.
Assessment: Testable, Clear

5.2.6. T2.2 Avoidance of Damage

T2.2 Avoidance of damage: ATLAS shall have sensing to ensure ATLAS stays in the operational zone.

Motivation: This requirement is presented to prevent damage of heritage and current projects. It is also in order to help guide the human operator when commanding ATLAS.
Means of Verification: Test - The team will ensure the chosen sensor provide accurate measurements by performing preliminary test.
Assessment: Testable, Binary only

T2.2.1 Physical Limit Sensing: ATLAS shall stop the motors when a physical limit has been reached via limit switches.

Motivation: Limit switches are desired to contain the CSCA in its functional range. Desire to protect heritage technology.
Means of Verification: Test - Activate the limit switch and confirm the motors stop.
Logic: The child requirement makes sense since it will prevent any motors from burning out and from ATLAS over or under extending. This design choice will also help the human operator know when the physical distance limits of ATLAS have been reached.
Assessment: Testable, Clear

T2.2.2 Non-Visual Confirmation the CSR Is Secure: ATLAS shall have digital sensors to indicate the CSR has been secured by the end effector.

Motivation: The team wants a way, other than visual, to confirm the CSR is securely grasped by the end effector.
Means of Verification: Test - Confirm securement is strong enough using a pressure sensor.
Logic: The child requirement makes sense since it will prevent any damage to the child scout rover. This design choice will also help the human operator know when to lift, or not life, the child scout rover. It will also help the human operator know when the end effector is in the correct position and orientation.
Assessment: Testable, Clear

5.2.7. T3.1 Remote Control

T3.1 Remote Control: ATLAS shall perform commands that are received from the GS.

Motivation: ATLAS requires commands from an operator for different phases of the mission. The operator will be located at the ground station.
Means of Verification: Test - The team will ensure ATLAS will execute commands sent by the GS by sending commands that will come up frequently.
Assessment: Unclear metric to measure the performance of the arm

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T3.1.1 Joint Station Keeping: The CSCA shall maintain its position without receiving commands.

Motivation: This is meant to make control easier as well as to ensure we do not drop the CSR on the ground.
Means of Verification: Test - The team will ensure the position of the CSR relative to the MR does not change when the MR is moving.
Logic: The child requirement makes sense since it is related to the action, or in this case lack of action, of commands being received from the ground station. ATLAS should also only move if the human operator is telling it to.
Assessment: Testable, Clear

T3.1.2 Deployment: The CSCA shall receive remote commands from the ground station to deploy the CSR.
Motivation: Remote control of the CSCA will allow for the CSR to be deployed from the MR.
Means of Verification: Test - The team will ensure the human operator can control ATLAS to deploy the CSR without damaging the CSR.
Logic: The child requirement makes sense since it is related to the action of commands being received from the ground station.
Assessment: Unclear metric that would be used to explicitly test damage caused to CSR

T3.1.2.1 Undocking: The CSCA shall be able to be remotely controlled by the GS in order to undock the CSR.
Motivation: Remote control of the CSCA will allow for the CSR to be undocked from the MR.
Means of Verification: Test - The team will ensure the human operator can control ATLAS to undock the CSR without damaging the CSR.
Logic: The child requirement makes sense since it is related to deployment of the CSR. If the team is unable to control the undocking of the CSR it cannot be deployed.
Assessment: Testable, Clear

T3.1.2.2 Stow: ATLAS shall receive remote commands from the ground station to stow the CSCA.
Motivation: The CSCA needs to be stowed when the CSR is deployed.
Means of Verification: Test - The team will ensure the human operator can control the CSCA moves back to a stowed position after deploying the CSR.
Logic: The child requirement makes sense since it is related to the phase just after deployment of the CSR. The arm must return to a stowed position so that the mother rover may complete its mission.
Assessment: Testable, Clear

T3.1.3 Retrieval: The CSCA shall receive remote commands from the ground station to retrieve the CSR.
Motivation: Remote control of the CSCA will allow for the CSR to be retrieved by the MR.
Means of Verification: Test - The team will ensure the human operator can control ATLAS to retrieve the CSR without damaging the CSR.
Logic: The child requirement makes sense since it is related to the functional requirement of performing commands because there is no autonomy in this project. Thus, ATLAS must be controlled by a human at all times.
Assessment: Unclear metric that would be used to measure damage to CSR if any, binary test possible.

T3.1.3.1 Docking: The CSCA shall be able to be remotely controlled by the GS to dock the CSR.
Motivation: Remote control of the CSCA will allow for the CSR to be properly stored on the MR.
Means of Verification: Test - The team will ensure the human operator can control ATLAS to dock the CSR without damaging the CSR.
Logic: The child requirement makes sense since it is related to the ground station controlling ATLAS to dock the CSR.
Assessment: Same as T3.1.3, unclear metric to measure damage caused to CSR, could make a binary test for damage.

T3.1.4 Ground Station UI: The ground station shall have a user interface.
Motivation: A user interface will help the human operator to facilitate control of ATLAS.
Means of Verification: Inspection - Verify UI is as expected.
Logic: The child requirement makes sense since if the UI is going to be used it must exist.
Assessment: Unclear metric to measure the quality of GUI, binary test possible

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T3.1.4.1 Directional Control: The ground station shall have remote manual control of the CSCA in the six Cartesian directions.
Motivation: The human operator shall be able to control the CSCA to move in all directions without using additional controllers.
Means of Verification: Test - The team will ensure the CSCA will move in the six Cartesian directions with commands from the human operator.
Logic: The child requirement makes sense since it is related to the mission statement of retrieving the CSR

when it is in the zone of operation. It must be able to move in 3D space to accomplish that.
Assessment: Binary testable, Clear

T3.1.4.2 Emergency Stop Button: The ground station shall have an emergency stop button that ceases movement of the CSCA within 0.5 seconds.
Motivation: An emergency stop button is required in case the limit switches or control law fail.
Means of Verification: Test - The team will ensure the CSCA will stop any movement within 0.5 seconds after the emergency stop button is clicked.
Logic: The child requirement makes sense since it is related to control of ATLAS. If the team is unable to stop ATLAS on command damage may occur to it or to a person.
Assessment: Testable, Clear

T3.1.4.3 Control of the State of the End Effector: The ground station shall have remote control of the state of the end effector.
Motivation: The GUI shall have a button to open and close the end effector.
Means of Verification: Test - The team will ensure the end effector is fully extended/fully retracted after receiving a command from the human operator.
Logic: The child requirement makes sense since it is related to the presence of a GUI.
Assessment: Binary testable, Clear

T3.1.4.4 Control of the Orientation of the End Effector: The ground station shall have remote control of the orientation of the end effector.
Motivation: The is to rotate the CSR for docking.
Means of Verification: Test - Test control of the rotary joint by moving it and measuring that rotation is as predicted by modeling.
Logic: The child requirement makes sense since it is related to the ability to command atlas, receiving , and docking.
Assessment: Testable, Clear

T3.1.4.5 GS Camera Display: The ground station shall display both camera outputs on the screen.
Motivation: This is to give us a 3D view of the CSR (one camera looking out and one looking down).
Means of Verification: Test - Check that the image is displaying the FOV we expect.
Logic: Two came output should be available simultaneously due to the design of the CSCA.
Assessment: Testable, Clear

T3.1.4.5.1 GS Camera Guidelines: The ground station display of the camera output shall have guidelines overlaid onto the images.
Motivation: Help with depth perception for controlling the ATLAS in all mission phases.
Means of Verification: Test - Test against rulers.
Logic: The child requirement makes sense since it is related to the ability of the human operator to move ATLAS. The guidelines will also help dock the child scout rover.
Assessment: Ability to test depth perception metric is unclear, possibly done with qualifiers respective to each individual participating in the test

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T3.1.4.6 GS Limit Switch Status: The ground station shall display all limit switch statuses.
Motivation: This is so the operator can know which limit switches have been triggered and not try to do something that will damage the CSR or MR.
Means of Verification: Test - Engage limit switches.
Logic: The child requirement makes sense since it is related to the fact that there is a present ground station, so it must be designed to work well for a human operator.
Assessment: Testable, Clear

T3.1.4.7 GS X,Y,Z Position of the End Effector: The ground station shall display the X,Y,Z position of the end effector in relation to the origin.
Motivation: This is to ensure safe deployment of the CSR.
Means of Verification: Test - Test encoder data by manually measuring position.
Logic: The child requirement makes sense since it is related to the fact that the end effector must be commanded to a position in order to receive code.
Assessment: Testable, Clear

T3.1.4.8 Safe Deployment and Retrieval: ATLAS shall overlay static video guidelines on visual data showing the zone the CSR may be in for retrieval/deployment.
Motivation: To help guide the operator when controlling the arm.
Means of Verification: Test - Check that the lines are showing the correct zone.
Logic: The child requirement makes sense since it is related to the fact that the CSR must be commanded in

order to move forward with the mission. This will be displayed on the ground station.
Assessment: Testable, Clear

5.2.8. T3.2 Data Handling

T3.2 Data Handling: ATLAS shall handle sensor data.

Motivation: Sensor data needs to be displayed in a way that is understood by a human operator at the GS.
Means of Verification: Test - If all children requirements to this requirement are verified, the data handling requirement is verified.
Assessment:

T3.2.1 Limit Switches: The CSCA shall process limit switch status data at critical points to prevent mechanical damage.

Motivation: Limit switches are desired to contain the CSCA in its functional range. Desire to protect heritage technology.
Means of Verification: Test - Activate the limit switch and confirm the motors stop.
Logic: The design requirement makes sense since the limit switches are sensors and the human operator needs to know their stats. They must be processed.
Assessment: Testable, Unclear in that it does not specify what the limit switch data is being used for in order to prevent mechanical damage. It does not clarify what ”shall process” means. In this instance the limit switch data would be read in by the Arduino and used to command the motors to stop all movement of ATLAS in order to ”prevent mechanical damage”.

T3.2.2 Distance Data Tolerance: ATLAS shall display the distance traveled by the end effector, based on stepper motor commands, within +/- 1 inches.

Motivation: The distance between the end effector and the ground will guide the human operator to control ATLAS. It will also prevent damage of the end effector and the CSR.
Means of Verification: Test - The team will ensure the converted distance is close to measured distance within ± 1”.
Logic: The design requirement makes sense since the stepper motor distance is a calculated distance and must be handled by ATLAS in order to be presented to the human operator.
Assessment: Testable, Clear

5.2.9. T4.1 ATLAS Two Way Communication

T4.1 ATLAS Two Way Communication: ATLAS shall engage in two way wireless radio communication with the GS.

Motivation: There must be two way communication to send information about the state of ALTAS and heritage to technology to the GS and also to send commands from the GS to ATLAS.
Means of Verification: Test - The team will verify by successful verification of children requirements
Assessment: Testable, Clear

T4.1.1 Range of Communication: The ATLAS communication subsystem shall communicate up to distance of 250 meters with the GS.

Motivation: Derived from the HERMES functional requirements. There may be trees or bushes in the way of communication.
Means of Verification: Test - The team will send communications two ways at varying distances up to a maximum of 250 m.
Logic: The design requirement makes sense since it defines the distance the two way communication network will work to.
Assessment: Testable, Clear

T4.1.1.1 Environment Attenuation: ATLAS communication subsystem shall maintain 8 dB of data margin with mission environment attenuation.

Motivation: If the signal is attenuated too much the signal will be lost and communications will break down. Characterization tests by HERMES with a factor of safety drive this requirement.
Means of Verification: Test - The team will send communications two ways at varying distances within the operational environment up to a maximum of 250 m.
Logic: The design requirement makes sense since ATLAS will be operating in an environment that will attenuate the signal.
Assessment: Testable, Clear

T4.1.2 Frequency: The ATLAS communication subsystem shall communicate with the GS in the 902-928 MHz frequency band.

Motivation: To ensure communication in the operational environment. There may be trees or bushes in the way of communication.
Means of Verification: Test - The team will send communications at varying frequencies within the operational environment.
Logic: The design requirement makes sense since it defines how the two way communication system will work, by defining the systems frequency band.
Assessment: Testable, Clear

T4.1.3 Data Rate: The communication subsystem shall communicate with the GS with a data rate of at least 6 Mbps.

Motivation: To ensure that the bandwidth is high enough to allow live video to be transmitted along with commands.
Means of Verification: Test - The team will send communications at varying bandwidths within the operational environment.
Logic: The design requirement makes sense since it defines how the two way communication system will work, by defining the data rate.
Assessment: Testable, Clear

T4.1.4 Data from ATLAS to GS: The ATLAS communication subsystem shall transmit sensor data from ATLAS to GS.

Motivation: Sensor data is needed for all phases of the mission. Thus, there will be a communication subsystem to transmit data from ATLAS to the GS.
Means of Verification: Test - The team will activate sensors and verify the reading is as expected.
Logic: The design requirement is a general statement defining what type of data will need to be sent over the two way communication system.
Assessment: Testable, Clear

T4.1.4.1 Visual Data: The ATLAS communication subsystem shall transmit visual data from ATLAS to the GS with a latency of less than 500 ms.

Motivation: Visual data is needed for deployment/retrieval phases of the mission. Thus, there will be a communication subsystem to transmit data from ATLAS to the GS.
Means of Verification: Test - The team will send visual data from ATLAS using cameras and ensure they are received by a laptop/GS.
Logic: The design requirement makes sense since it defines what will be sent and how it will be sent across the communication system. Another reason why two way communication is needed.
Assessment: Testable, Clear

T4.1.4.2 Limit Switch Status: The ATLAS communication subsystem shall transmit limit switch status from ATLAS to the GS.

Motivation: Limit switch status data is needed for all phases of the mission. Thus, there will be a communication subsystem to transmit data from ATLAS to the GS.
Means of Verification: Test - The team will test that accurate data is sent when the limit switch is activated.
Logic: The design requirement makes sense since it defines the type of sensor data that will be sent, T4.1.4. This another reason why two way communication is needed.
Assessment: Testable, Clear

T4.1.5 Commands from GS to ATLAS: The ATLAS communication subsystem shall transmit commands from GS to ATLAS.

Motivation: Commands must be sent to ATLAS to do the mission.
Means of Verification: Test - Send commands and test that ATLAS behaves as expected.
Logic: The design requirement makes sense since it defines what the two way communication will be used for.
Assessment: Testable, Clear

5.2.10. T5.1 ATLAS Power

T5.1 ATLAS Power: ATLAS power subsystem shall provide power to subsystems

Motivation: ATLAS will not function without power.
Means of Verification: Analysis - If all children requirements are verified this requirement is verified
Assessment: Testable, should have listed subsystems

T5.1.1 Sensing Subsystems: The sensing subsystems shall have the power accessible for the duration of the mission.

Motivation: CSCA needs sensors to pick up the CSR.
Means of Verification: Test - Test the sensors subsystems' capability to perform their specific function in relation to completing ATLAS' mission.
Logic: The design requirement makes sense since it powers the sensor subsystem needed to mitigate damage to current/heritage technology.
Assessment: Testable, Clear

T5.1.1.1 Camera Voltage and Current: The ATLAS power subsystem shall provide DC 5 Volts and 180 mA to both of the FPV cameras.

Motivation: The CSCA power subsystem must power the individual electrical components with the voltage and current as specified by the electrical component's data sheet.
Means of Verification: Test - Measure that the cameras receive required power and current.
Logic: The design requirement makes sense since it defines the power requirements for the camera subsystem.
Assessment: Testable, Clear

T5.1.1.2 Limit Switches Voltage and Current: The ATLAS power subsystem shall provide 3.3 Volts to all Limit Switches integrated in the sensor subsystem.

Motivation: The CSCA power subsystem must power the individual electrical components with the voltage and current as specified by the electrical component's data sheet.
Means of Verification: Test - Measure that the limit switches receive required power and current.
Logic: The design requirement makes sense since it defines the power requirements for the limit switch subsystem.
Assessment: Testable, Clear

T5.1.2 Controls Subsystems: The control subsystems shall have the power accessible for the duration of the mission.

Motivation: CSCA needs controls to pick up the CSR.
Means of Verification: Test - Test the controls subsystems' capability to perform their specific function in relation to completing ATLAS' mission.
Logic: The design requirement makes sense since it identifies that power must be available for the duration of the mission. This is also required for constant communication.
Assessment: Testable, Clear

T5.1.2.1 Microcontroller Voltage and Current: The ATLAS power subsystem shall provide DC 7-12 Volts and 800 Milli-Amperes to the microcontroller(s).

Motivation: The CSCA power subsystem must power the individual electrical components with the voltage and current as specified by the electrical component's data sheet.
Means of Verification: Test - Measure that the microcontrollers receive required power and current.
Logic: The design requirement makes sense since it defines the power requirements for the microcontroller subsystem.
Assessment: Testable, Clear

T5.1.2.2 Motors Voltage and Current: The ATLAS subsystem shall provide 24 Volts and 5.54 Amperes to all motors mounted to the CSCA structure.

Motivation: The CSCA power subsystem must power the individual electrical components with the voltage and current as specified by the electrical component's data sheet.
Means of Verification: Test - Measure that the motors receive required power and current.
Logic: The design requirement makes sense since it defines the power requirements for the motor subsystem.
Assessment: Testable, Clear

T5.1.3 Communications Subsystems: The communication subsystems shall have the power accessible for the duration of the mission.

Motivation: CSCA needs to be commanded in order to pick up the CSR.
Means of Verification: Test - Test the communications subsystems' capability to perform their specific function in relation to completing ATLAS' mission.
Logic: The design requirement makes sense since it defines the power requirements for the communication subsystem.
Assessment: Testable, Clear

T5.1.3.1 SBC Voltage and Current: The ATLAS power subsystem shall provide DC 5 Volts and 3 Amps to the SBC (ASUS Tinkerboard).

Motivation: The CSCA power subsystem must power the individual electrical components with the voltage and current as specified by the electrical component's data sheet.

Means of Verification: Test - Measure that the SBCs receive required power and current.
Logic: The design requirement makes sense since it defines the power requirements for the SBC subsystem.
Assessment: Testable, Clear

T5.1.3.2 POE Voltage and Current: The ATLAS power subsystem shall provide DC 9-12 Volts and 2 Amperes to the POE modules (GS and CSCA).
Motivation: The CSCA power subsystem must power the individual electrical components with the voltage and current as specified by the electrical component's data sheet.
Means of Verification: Test - Measure that the POE receive required power and current.
Logic: The design requirement makes sense since it defines the power requirements for the POE subsystem.
Assessment: Testable, Clear

T5.1.4 Off Switch: The power subsystem shall have a mechanism for an operator to stop power flow.
Motivation: In the event of emergency or maintenance/repair operators should be able to work in a power-safe environment. A safety mechanism should be in place. This is essentially an off switch.
Means of Verification: Test - Measure that voltage and current stops when the off switch is activated.
Logic: The design requirement makes sense since it defines the power requirements for the off switch subsystem.
Assessment: Testable, Clear

T5.1.5 Electrical Housing: Electrical housing shall allow unrestrained movement of hardware.
Motivation: Avoiding damage from unexpected environmental factors and potential electrical mishaps.
Means of Verification: Test - Run electrical systems and make sure hardware is not impacted by housing of wiring and electronic components.
Logic: The design requirement makes sense since it defines the need to house electronics in a way that will not inhibit ATLAS or heritage technology.
Assessment: Testable, Clear

5.2.11. L1.1 HERMES Capabilities

L1.1 HERMES Capabilities: ATLAS shall allow HERMES systems to remain the same by only modifying the top plate of the CSR.
Motivation: HERMES original systems will be untouched to ensure it may complete its mission. The only change is the removal of a non-mission critical cover. A weight bearing frame will be implemented to in its place.
Means of Verification: Analysis - The team will do analysis/inspection on each component of HERMES that ATLAS interacts with.
Assessment: Testable, Clear

L1.1.1 Interface Plate: ATLAS shall interface with HERMES via an interface plate qualified to support the mass of the CSR during the mission.
Motivation: The interface plate must be able to support the weight of the CSR during retrieval, carrying, and deployment.
Means of Verification: Analysis - Verification test of interface plate using weight similar to CSR.
Logic: The child requirement is directly linked to the parent requirement in that they both are directly related to the child scout rover interface plate. This design requirement discusses how the interface plate will be modified.
Assessment: Testable, Clear

5.2.12. L1.2 DRIFT Capabilities

L1.2 DRIFT Capabilities: ATLAS shall allow DRIFTs systems to remain the same by staying away from DRIFT systems.
Motivation: We need to maintain the capabilities of DRIFT while completing ATLAS mission objectives in order for the full Fire Tracker system to operate as a cohesive unit. This applies to all phases of the mission.
Means of Verification: Analysis - The team will do analysis/inspection on each component of DRIFT that ATLAS affects.
Assessment: Testable, Consider replacing ”staying away” with a more definitive and affirmative terminology such as ”eliminating interaction with”.

L1.2.1 Mount Arm on Frame: ATLAS shall be mounted on the MR frame such that it is not in the zone of operation of the landing platform.

Motivation: This will define the location that ATLAS can operate without interfering with other systems.
Means of Verification: Analysis - Measure that ATLAS is in the prescribed zone.
Logic: The design requirement makes sense in that it will ensure that DRIFT's systems remain the same.
Assessment: Testable, Clear

L1.2.1.1 Slope Stability: ATLAS shall allow the MR to maintain its balance while carrying the CSR on a 20° slope in any heading.
Motivation: DRIFT should not tip over on a downwards slope with the addition of ATLAS to the MR.
Means of Verification: Analysis - Confirm that ATLAS does not cause the CG of DRIFT to move beyond acceptable limits on a 20° slope either when the CSR is docked or when just the CSCA is stowed.
Logic: The design requirement makes sense in that it will ensure that DRIFT's systems remain the same. DRIFT shall still be able to traverse 20° slopes in any heading. This is directly linked to L1.2.1, since the way the frame is mounted could affect DRIFT's ability to move up and down the specified slope.
Assessment: Testable, Clear

L1.2.1.2 Environmental Sensing: ATLAS shall remain outside of the FOV DRIFT's camera.
Motivation: DRIFT sensors must not be blocked or knocked out of alignment.
Means of Verification: Analysis - Confirm that ATLAS does not obstruct the FOV of the DRIFT camera using DRIFT documentation.
Logic: DRIFT needs its camera unobstructed in order to traverse.
Assessment: Testable, Would rewrite so that ATLAS can be in the FOV of DRIFT's camera, but not obstruct the operators ability to see from the DRIFT in order to command the mother rover.

L1.2.1.3 Mother Rover Tipping: The MR shall remain upright while lifting the CSR.
Motivation: If the MR tips over the mission is a failure.
Means of Verification: Test - This will happen while testing the lifting capabilities of ATLAS.
Logic: The mother rover, not only has to handle moving with a docked child scout rover, but it must be able to stay upright when lifting the child scout rover. Otherwise, DRIFT would not be able to continue its mission.
Assessment: Testable, Clear

L1.2.1.4 DRIFT Object Traversal Ability: The portion of ATLAS permanently fixed to DRIFT shall stay above 6" from the ground to allow MR clearance of obstacles.
Motivation: The wheels and the ground clearance of HERMES allow it to pass over obstacles. This zone will allow the CSR to hang off the side but be high enough to not obstruct the 5" clearance of the MR.
Means of Verification: Analysis - Confirm that no part of ATLAS obstructs DRIFT 5" of clearance.
Logic: In order for DRIFT to complete its mission ATLAS will stay away from DRIFT's clearance height.
Assessment: Testable, Would add, "during traversal" to clarify that the requirement only applies to when the mother rover is moving.

5.2.13. L1.3 CHIMERA Capabilities

L1.3 CHIMERA Capabilities: ATLAS shall allow CHIMERA systems to remain the same by staying outside of the zone of CHIMERA operation.
Motivation: We need to maintain the capabilities of CHIMERA while completing ATLAS mission objectives in order for the full Fire Tracker system to operate as a cohesive unit. Staying out of the zone of CHIMERA will allow it to complete its mission.
Means of Verification: Analysis - Define zone and use CAD to see nothing is inside it
Assessment: Testable, Make clearer by describing the zone of operation within the requirement.

5.3. Resulting Design

Figure 8 below shows the complete ATLAS system, along with the integration with some of the heritage projects shown in blue. The major subsystems of the resulting design include the hardware, software, and electronics subsystems.

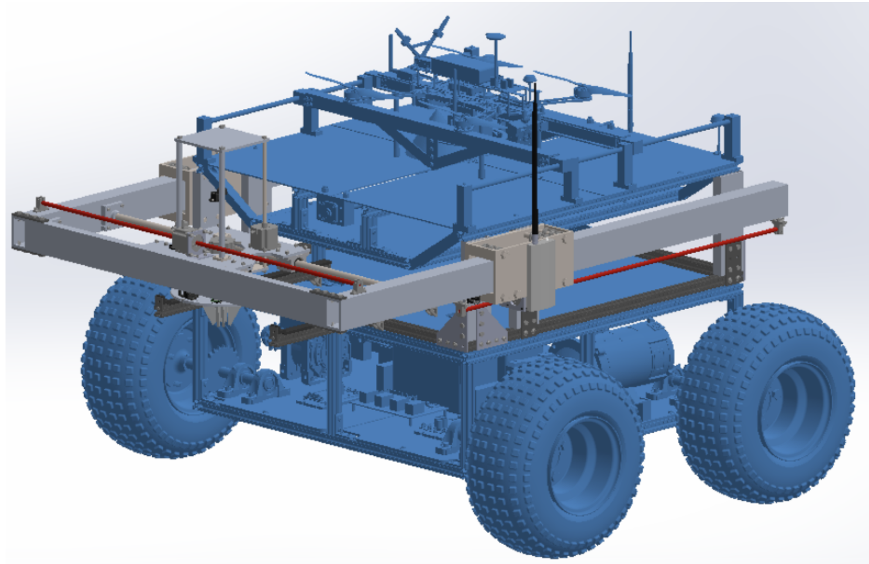


Figure 8: ATLAS and Heritage Projects

5.3.1. Hardware

The final hardware design included the following components: the extension frame, transverse frame, vertical frame, end effector, rotary joint, child scout rover interface plate, and the mother rover interface. The latter is described in more detail below.

a. Extension Frame The extension frame consists of four major mechanical components. The first being two aluminum extension beams shown in Figure 8 with dimensions presented in table 3 below. The lengths of the extension beams were designed such that ATLAS could extend its end effector to one meter. The second component is the linear guide-rail and slide assembly, which is the primary mechanism that provides the desired linear motion to the extension frame. Note that there are two of these assemblies, one on each side of the extension frame. The third component is two custom, ball-bearing roller assemblies. These roller assemblies were designed primarily to support the large expected loads that are transmitted through the extension beams to the Mother Rover interface locations. In addition, they were designed to provide supplemental linear guidance to the guide-rail and slide assembly systems. The final component of the extension frame is the cross support beam that connects the two extension beams together. The beam is mounted to the two extension beams via four aluminum brackets, each with four 1/4”-20 bolts.

Table 3: Extension Frame Component Specifications

Component	Material/Type	Length (in)	Cross section (in)	Thickness
Extension beams	Al 6061-T6 rectangular tubing	58.5	2.0 x 3.0	0.250
Cross support beam	Al 6061-T6 rectangular tubing	38.42	1.0 x 3.0	0.125
Ball-bearing roller assembly	4130 alloy steel plate	N/A	5.125 x 10.125	0.25
Linear guide-rail assembly	Al 6061 w/ steel rails	34	N/A	N/A

b. Transverse Frame The transverse frame will control the lateral movement of the hard capture mechanism relative to the mother rover in the gantry crane system. The transverse frame has the capability of traversing approximately 27”. The transverse frame is primarily composed of two steal supporting rails, a NEMA 23 Non-Captive motor and its corresponding lead screw, bolts to interface with the extension frame, and pillow-blocks.

c. Vertical Frame The vertical frame is responsible for actuating the end effector of ATLAS vertically. In order to do so, the vertical frame is integrated with the end effector to provide a stable interface. The vertical frame also interfaces with the transverse frame. The pillow blocks located under the vertical frame’s main platform provide a minimal friction surface that allows it to be actuated.

The vertical frame consists of a main plate, a supporting plate, 3 supporting guided rails which each run through a linear bearing, a NEMA 23 Non-Captive Motor and corresponding lead screw, and 2 pillow-blocks.

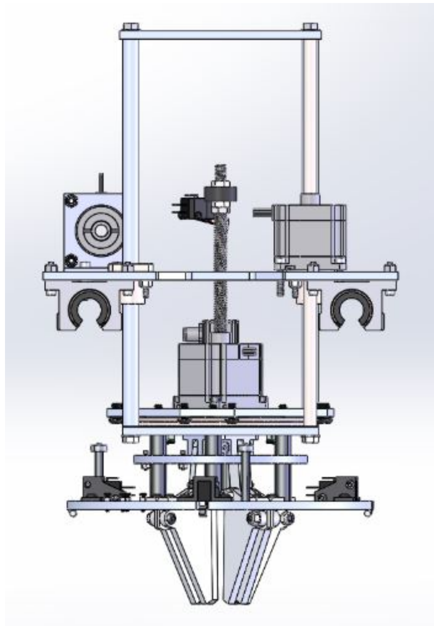


Figure 9: Vertical Frame Design Solution

d. End Effector The end effector interfaces with the HERMES child scout rover (CSR). This hard-capture mechanism has the ability to capture the CSR, holding it so it can be maneuvered to and from a docked position on the MR. The end effector utilizes a NEMA 23 stepper motor with a non-captive lead screw system, which allows for accurate linear actuation. The four 'petals' shown in blue in Figure 10, start in an open position. ATLAS' vertical frame then lowers the end effector petals through the CSR interface hole until the end effector backplate touches the CSR interface plate, at which time 4 limit switches are triggered. These limit switches ensure that the end effector is in the correct position to grasp the CSR. The NEMA 23 linear motor then actuates the lead screw downward, which it attached to a central hub connecting the four petal linkages. As these linkages are forced to move toward a horizontal position, the petals clamp onto the CSR interface plate as shown in Figure 11.

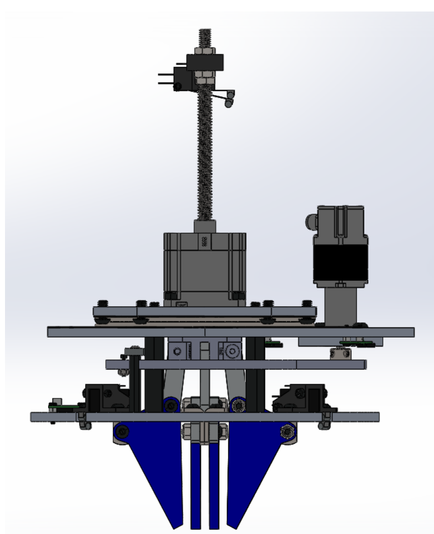


Figure 10: Hard Capture Open Orientation

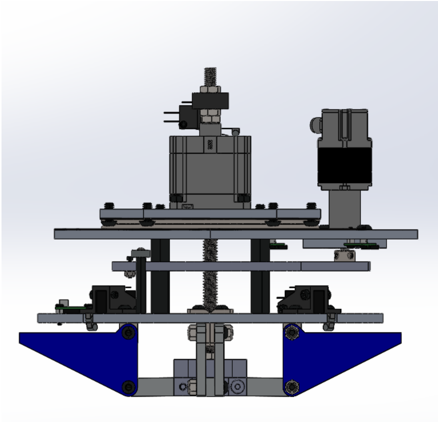


Figure 11: Hard Capture Closed Orientation

e. Rotary Joint The ATLAS rotary joint allows for the reorientation of the CSR during the recovery phase of the mission. The joint utilizes a modified Lazy Susan in conjunction with a NEMA 11 stepper motor and planetary gearbox to rotate the captured CSR through 180 degrees of rotation about the long axis of the mechanism.

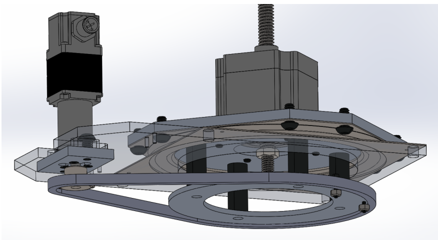


Figure 12: End Effector Rotary Mechanism (Note: Petals and interface plate omitted for clarity)

This process enables the retrieval and successful docking of the CSR, regardless of the initial orientation, and enables greater flexibility in mission environments. Prior to lowering the hard capture mechanism, the rotary joint is used to line up the normal directions of the CSR and hard capture mechanism.

f. Child Scout Rover Interface Plate The CSR upper plate and structure were modified to enable the acquisition and carrying of the CSR by ATLAS. The old non-loadbearing acrylic upper structure was replaced with a robust aluminum plate and 80-20 frame. The hole in the upper plate enabled the capture of the CSR via the end effector petals, which would reach through and grab the plate securely.

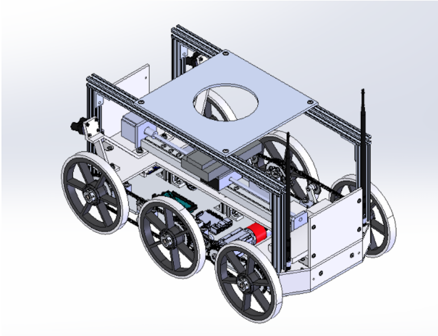


Figure 13: CSR Interface Plate)

g. Mother Rover Interface This structure provides a critical anchor point via which ATLAS can mechanically interface with the Mother Rover. This will ensure ATLAS remains physically attached to the Mother Rover during all phases of the mission. The Mother Rover interface can be broken up into two major components, the front mounting structure and the back mounting structure.

The front mounting structure consists of four 9.5" tall Al 6061-T6 rectangular bars (two on either side), each with a 3" x 2" cross section. These serve as the four primary supports for which both roller assemblies are mounted to. The six 1/2" steel bolts which serve as the ball-bearing roller shafts are bolted into these supports, creating a robust anchor point. These four support beams are then mounted the the Mother Rover's 80/20 chassis via a series of 3/16" thick anodized aluminum brackets with 1/4"-20 bolts.

The back mounting structure is the second major component of the fastening system. It consists of two 9.5" tall Al 6061-T6 supports (one on either side) that are mounted to the Mother Rover's 80/20 chassis via the same aluminum brackets. However, note that these two supports have rectangular tubing cross sections with dimensions: 3" x 2" x 1/4". These supports are designed as an actor point for which the linear guide-rail is mounted to as shown in the figure. Since the guide-rail is a redundant load bearing system (second to the roller assemblies), it was determined that aluminum tubing provides sufficient mounting capabilities for the maximum expected loading on the guide rail which is ultimately transferred into the two supports.

5.3.2. Electronics

a. Microcontroller Unit - Data Handling The Microcontroller (MCU) that was used in the design was chosen to be the Arduino Due. This MCU is capable of handling both digital and analog inputs and outputs. It can also communicate with other devices via Serial Peripheral Interface (SPI), I2C, and UART interfaces. It accepts 9V DC power and draws less than one amp of current. It was capable of receiving commands from and sending data to the single-board computer.

The MCU was part of the design because ATLAS needed to have the ability to read sensor data and send commands to at least five motors on the arm. In order to do this, the team needed an MCU that could accept many digital inputs from limit switches and Hall Effect sensors. The Due is sufficient for both of these tasks because it has 54 digital input/output (I/O) pins as well as SPI and UART communication capabilities. Finally, the electronics team selected the Arduino Due because it was capable of keeping up with the processing.

The mechanical components of the MCU included the Arduino Due and a USB cable for connecting between the SBC and MCU.

b. SBC - Data handling The SBC would coordinate data flow across all the systems of ATLAS. Data would go through the SBC for either packetization, sending, or receiving. The SBC possessed the computing power to handle the two video feeds from the sensor system on ATLAS. The amount of data transmitted by the cameras would surpass the capabilities of the Arduino and this was the primary motivation of using a SBC like the ASUS Tinkerboard. Additionally, the ASUS Tinkerboard provided the ethernet hardware capability for direct access to the antenna. This was used on ATLAS for wireless communication to the ground station. The hardware on the ASUS Tinkerboard also enabled direct access to the Arduino via a serial USB connection, which would allow sensor data and ground station commands to be sent between the two boards.

The ASUS Tinkerboard is a singular and complete system by itself. The board only requires a power supply, ethernet connection (cable input), and a USB serial connection to the Arduino DUE in addition to each of the two cameras. The board has a processor, memory, and the Input/Output connections all self contained on the board and requires no custom manufacturing to ensure full functionality.

c. Power Subsystem The power system was broken up into separate powered elements so that each sub-element could be individually tested. This also eliminated the possibility of ruining delicate hardware through an accidental connection to an unregulated power supply. The design ensured that each electrical element was only connected to a power supply that offered a regulated voltage and current specific to the element that required power. As an example, the Arduino DUE will accept 7-12V DC through a barrel jack connection. The TalentCell is capable of outputting this acceptable voltage through a barrel jack and additionally provides the capability of a 5V USB connection which is satisfactory for the ASUS Tinkerboard. The Mother Rover would be segregated from ATLAS using several 6 Amp slow-triggered fuses which would ensure that the motor driver carriers would not be damaged.

The Mother Rover's power supply, consists of two 12V 100Ah batteries wired in series which provide a total voltage of 24V and 200Ah of capacity. The C&DH system is powered by one TalentCell 6000mAh battery. The integrated 7-12V DC output barrel jack will supply the necessary power to the Arduino DUE. The 5V USB out will provide the required power to the ASUS Tinkerboard SBC. The last power bank is another 6000mAh TalentCell battery which will be connected to the POE (Power Over Ethernet) to provide power to the antenna.

d. Motor Driver Carrier The motor drivers are necessary to separate the electrical components of the Arduino DUE from the relatively high current and voltages required by the motors. The Arduino DUE is only operating at approximately 800mA which is more than six times less than the peak current drawn by a single motor during operation. The high current would ruin the Arduino DUE if the motors were wired directly to the board.

The Pololu motor driver carriers used in the design are enabled with SPI (Serial Peripheral Interface), this allows the drivers to be controlled using several common connections across all of the peripherals from the Arduino DUE. The SPI capability severely cuts down the required number of digital Input/Output pins required from the Arduino to control each of the drivers. Each driver will be able to share 3 pins on the DUE and then an addition pin per driver will also be necessary. The SPI protocol uses 4 lines: Master-out Slave-in, Master-in Slave-out, Chip Select, and Clock signal. The serial data out line carries data from the microcontroller to the peripheral (motor driver) and is used to modify the settings of the driver and command specific motor actions: number of steps or stepping speed. The Master-in slave out pin will be used to transmit the error messages back from the drivers based on over heating or over current cases. This data is likely to be unused for actual operation as there is not plan to operate the drivers at a dangerous level of current draw which might cause the over heating fault case. The common clock line is used on the SPI protocol to keep the data transfer in a rigid timing structure so that data is only sent when the receiver is ready and vice versa. For ATLAS, there will be a chip select line going to each individual motor driver, this is one of the few connections in the SPI interface that needs individual lines running to each element. The other communication line that will be used for the motor driver carries is the SLA pin on each board. These are analog pins that will output a relative voltage related to the back electromotive force induced in the driver based on motor actuation. With the SLA voltage measurement, the load on the motors and the relative output force of the motors can be determined.

e. Communications The communication system allows for wireless radio control of ATLAS from the ground station and transmission of data and video in the other direction. The system is able to communicate at a range of 250 meters through the mission define forest environment in the 900 MHz frequency range. The radios used are the same as those on board HERMES. This will allow the HERMES GS hardware to be used for ATLAS and avoids interference between ATLAS and HERMES communications. The communication system primarily consists of a pair of Ubiquiti Rocket M900 radio with attached antennas. The radios are powered by a power-over-ethernet injector with a dedicated battery. Figures 14 and 15 show the overall setups for the communications on board ATLAS and for the GS. The components that make up these setups are labeled and will be described individually. The FBD for the communication system is shown in Figure 16.

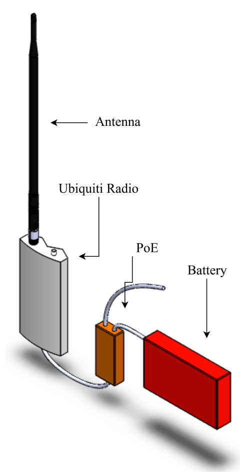


Figure 14: Model of the ATLAS Communication System On Board the MR

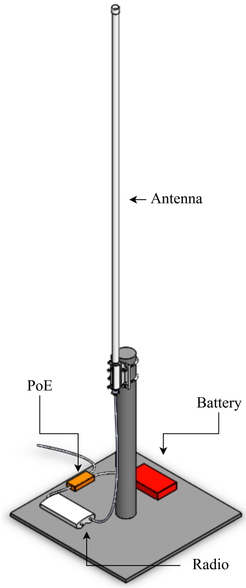


Figure 15: Model of the GS Communication System

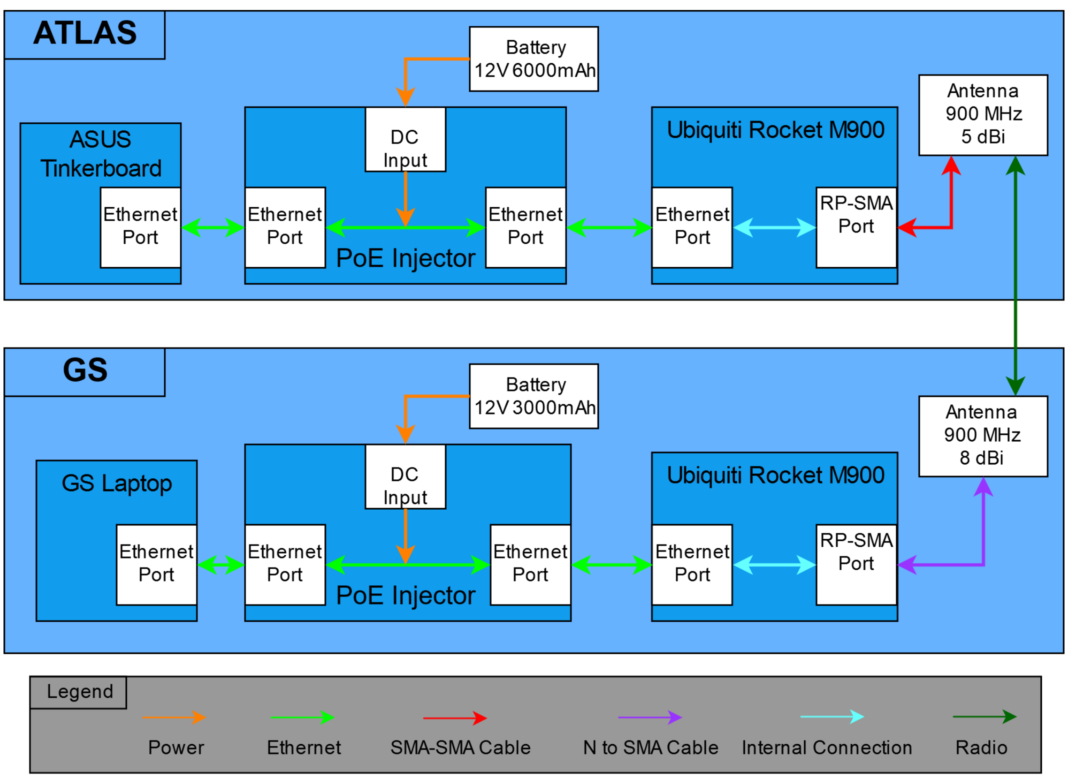


Figure 16: Communication System FBD

The radios that ATLAS will use are Ubiquiti Rocket M900s that allow for the formation of wireless networks over long distances. They operate in a frequency range from 902-928 MHz. This frequency band is left open by the FCC for amateur use. T4.1.2 requires that we do not operate outside this band.

The M900 uses IEEE 802.11n wireless networking standard as a communication protocol with configurable modulation of MCS0 to MCS15 with a 20 MHz bandwidth. Requirement T4.1.3 requires that the communication system have a data rate of at least 6 Mbps. By modulating the signal at MCS1, the M900 can achieve up to a 14.4 Mbps data rate, satisfying this requirement.

The GS and ATLAS use different antennas. ATLAS uses the L-Com HG905RD-SM, a 16.9” 5 dBi rubber duck omni-directional antenna that was also used by HERMES. The GS will use the L-Com HG908UP-NF, a 57.3” 8 dbi omni-directional antenna.

To power the Rocket M900s on ATLAS and the GS, 2 Tycon Systems TP-DCDC-1224 PoEs will be used. These will allow power to be transmitted through the ethernet cable to the M900s. Each PoE is in turn powered by a dedicated TalentCell 6000 mAh battery.

Requirements T4.1.4, its sub-requirements, and T4.1.5 require specific data be able to be transmitted in both directions between ATLAS and the GS. T4.1.4.1 specifically requires that the maximum latency of the transmitted data not exceed 500 ms. From the HERMES test data, the maximum latency using similar equipment was found to be 226 ms through 250 m of trees [15]. As ATLAS will use similar components to HERMES, the same latency is expected for ATLAS which will satisfy the T4.1.4.1 requirement.

f. Video and Field of View The purpose of having a specified field of view, is to ensure that the human operator can operate ATLAS and complete the mission. The following functional requirement is what drives the design choice of having a field of view of 120°. This also drives the design choices concerning the resolution and frames per second.

The component regarding the latter requirement includes just the ordered USB camera, ELP megapixel Super Mini 720p USB Camera Module. The camera can be seen, with detailed specifications, in Figure 21 in section 7.3.2.

5.3.3. Software, Control and Data Handling

a. Final Software Selection In order to develop software to meet all requirements, open source libraries are utilized. Based on the selection of the microcontroller, Arduino language is used for the stepper motor control. With the help of motor drivers, Arduino allows for switching speed and direction of multiple motors synchronously. Additionally, Arduino has built-in functions to handle serial input and output through the USB port. It allows for communication between the Tinkerboard and Arduino. Commands and live data are sent through this serial communication. On the Tinkerboard, python scripts are used to pass the commands from the ground station and handle the sensor data. In order to have the script compatible with Arduino's serial communication, Python serial library was selected. It also allows for sending/receiving data from the USB port when the port name is identified.

To capture the video stream from cameras, FFMpeg Library was determined to be the video streaming software. FFMpeg allows for compressing the camera video output into several formats with desired resolution and frame rate. Also, it has the functionality to work together with video player on the ground station which is OpenCV. With FFMpeg and OpenCV, the developer does not have to determine the codec (encoding and decoding method) for the packetization because FFMpeg will find the optimized codec based on the server and client's system specifications as inputs. Since the communication between the Tinkerboard and the ground station computer is wireless, Python socket library is used to establish connections. Python socket has the ability to packetize/depacketize data in multiple formats. It also allows for utilizing common protocols like TCP and UDP to send/receive data in readable ways.

On the ground station, as mentioned before, OpenCV is used to depacketize video data sent from the Tinkerboard using FFmpeg. After coded video frames are recovered, OpenCV can render the frame data on the screen while adding guidelines to help the human operator. For the GUI (Graphical User Interface) design, Python Kivy was selected because it allows the OpenCV to display the video on the canvas created by Kivy. Additionally, Kivy has functionalities to create dynamic buttons and data displays while not having a separate script running. For tracking the user input, Python Pynput library was found to be capable of listening to keyboard changes in an allowable latency.

b. Software Interfaces One of the most difficult aspects of software is how components interface with each other. For the serial connection between the Arduino and the Tinkerboard, the team decided to use Arduino's default codec which is ASCII. Even though ASCII can represent less characters than the utf-8, it is sufficient for this project considering the amount of commands that are sent through. The baud rate is set to be 9600 bps. Since only commands and limit switch status are sent between the Arduino and the Tinkerboard, this rate provides a tolerable amount of bandwidth.

For the live video data from the camera to the ground station, the FFMpeg library decides the codec and pixel format based on the hardware specs and the connection quality of the network. The rate that packets are sent at depends on the desired frame rate of the video. To meeting the requirement T2.1.4, a frame rate of 20 fps is needed. So the video is sent at a rate of 20 packets per second. The wireless connection between the Tinkerboard and the ground station requires network protocols to define the rules that govern network communication. The commands and limit switch status were determined to use the TCP protocol. This selection is based on the requirement that ATLAS shall perform commands that are received from the ground station. The multi-step handshakes that the TCP protocol has can ensure all the commands and data will be received at a latency which depends on the connection and the packet size. Because commands and sensor data are coded short strings, it is unlikely for the latency to become significant. However, the packet size for the video transmission is much bigger compared to the command packet size. The handshaking process will cause a noticeable delay to the human operator. To meet the requirement that the ATLAS shall transmit visual data with a latency of less than 500 ms, the UDP protocol is used for the video transmission. The UDP protocol allows for faster connection but may have some packet loss. It was considered that the packet loss for video transmission was only an instant frame rate drop, the human operator was still able to get visual feedback. So the UDP protocol is more capable of meeting requirements.

c. Ground Station User Interface A graphical user interface on the GS is necessary to meet the following functional requirements. These requirements relate to the display of information used for helping the human operator command ATLAS remotely.

The design and implementation of the graphical user interface will be done using the Python Kivy library. For the user keyboard inputs, Kivy was also used to track keyboard events.

In order to satisfy the design requirement of having a graphical user interface, the library used needs to have the functionality of dynamically rendering the interface and displaying data. Kivy is an open-source library designed for app development across platforms like Windows, MacOS and mobile devices. It is known for its highly interactive user interfaces. Figure 17 shows a diagram of full life cycle of a Kivy app. Because Kivy's excellence of designing reactive apps, the diagram uses iOS and Android as an example. The latency is an important factor in the success of the human interaction. The reception of the sensor status and live video is not the only thing that affects the latency of the human operator receiving the feedback, the time it takes to render the data on to the graphical interface will also add up to the total amount of latency. So having a mobile-level responsive user interface is necessary for this project.

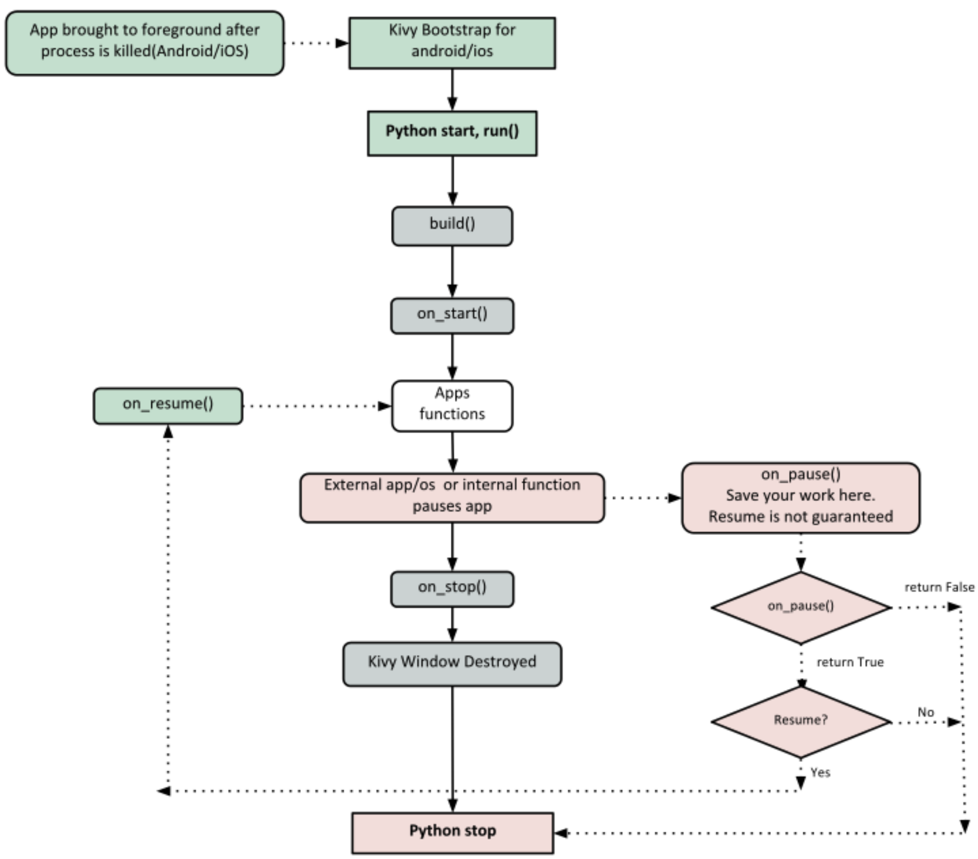


Figure 17: Kivy App Life Cycle[37]

Additionally, Python Kivy allows for displaying videos or images from video players outside the Kivy classes. In this project, OpenCV is used to decode provided processed frames for Kivy to display live videos on the canvas. Figure 18 is an example of Kivy displaying a video stream from a webcam.

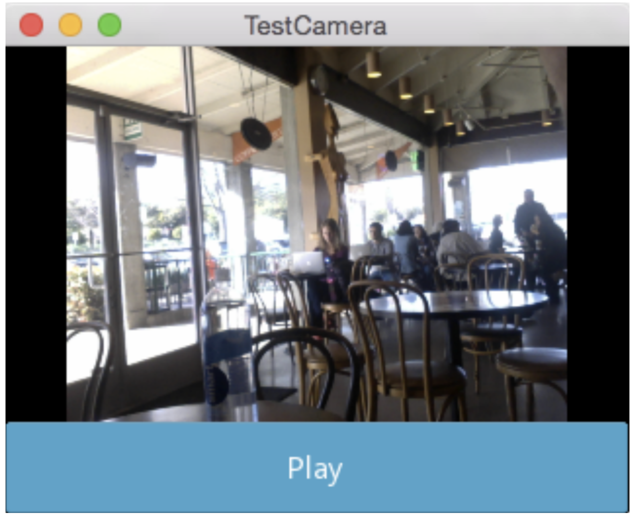


Figure 18: Kivy Video Display

Below is a preliminary design for the graphical user interface. This design shows the live video feed, sensor statuses, end effector status and position, and an instruction to the human operator to meet the design requirement T3.1.4. After the design has been implemented, it will be tested with subjects who are unfamiliar with how to control ATLAS to ensure the accessibility of the GUI.

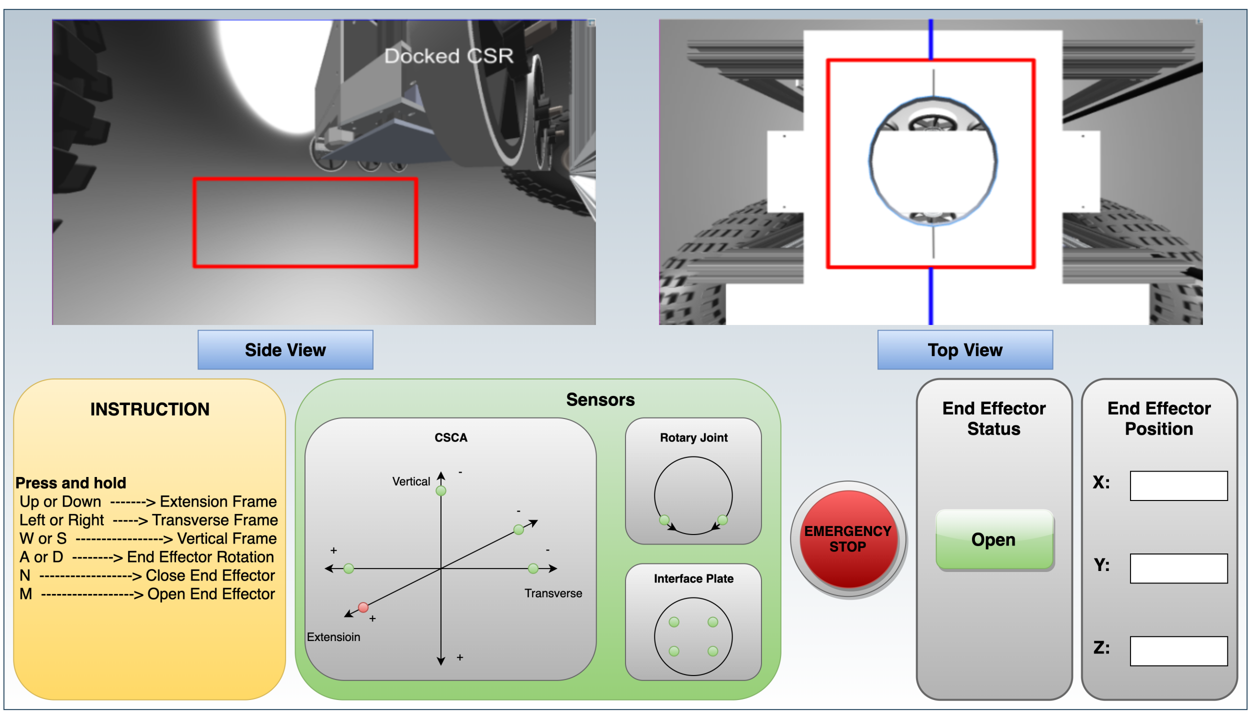


Figure 19: Preliminary GUI Design

The Kivy library allowed the user to input keyboard commands to be read directly into the GUI. The current design is to only use keyboard inputs to command ATLAS. Mouse tracking might be considered in the next semester as a higher level of success. Figure 20 shows a flow diagram that simulates the entire process of sending commands to the Arduino from keyboard inputs. The Tinkerboard is used as the server to receive coded commands then send them to the Arduino through serial communication. The ground station works as a client that collects changes in keyboard inputs in this case.

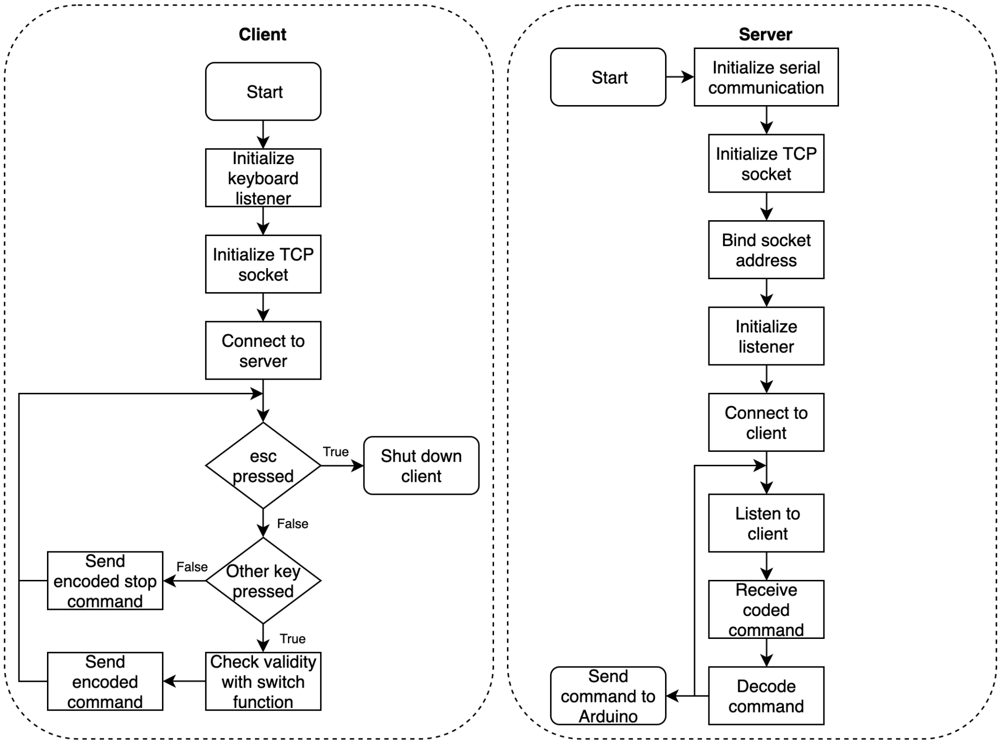


Figure 20: Command Flow Diagram

d. Position Feedback The position feedback system of ATLAS is made up of limit switches (traditional roller and hall effect sensor switches with corresponding magnets) and two video cameras. The parts are listed below with the relevant specifications. Using Python, in conjunction with OpenCV, guidelines will also be added to the live video feed.

Figure 21: ELP megapixel Super Mini 720p USB Camera Module

Specifications:

- FOV: 120°
- Size: 26mm x 26mm/32mm x 32mm (optional)
- Power: DC 5V
- Support OS: Windows, Linux with UVC, Mac OS, and Android
- Compression Format: MJPEG or YUY
- Max Resolution: 1280 x 720p, 1 mega pixel
- Sensor: CMOS 1/4' inch OV9712
- Interface: USB

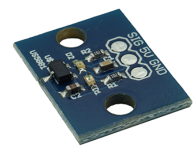


Figure 22: Hall Effect Sensor Board from Westcoast Products

Specifications:

- CAD of Piece available
- Signal: Digital
- Connector: 3x1 - .1”; Header
- Battery: 5-6V
- Sensing Distance .125”-2”

Figure 23: Magnet from Westcoast Products

Specifications:

- Size: .125” ID x .500” OD x .125” WD
- Type: Ring

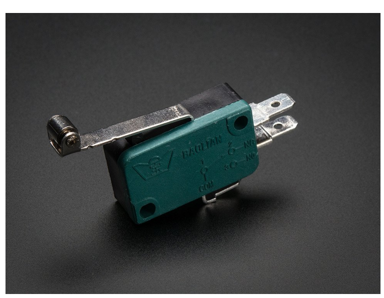


Figure 24: Micro Switch with Roller Lever from Adafruit

Specifications:

- Size: 50.8 mm x 30.2 mm
- Terminal Width: .187"

The limit switches are located at the extreme points of every frame (extension, transverse, and vertical). There are also five total limit switches on the end effector. There are four on the back plate of the end effector, in order to confirm that contact has been made with the child scout rover interface plate. There is one on the vertical lead screw, which actuates the end effector. This is to confirm that the petals have been fully extended and the child scout rover is being secured by the end effector. Lastly, there are two hall effect switches on the end effector also, to sense the rotation of the end effector.

Below is a high level flow chart which steps through how the limit switch data (and hall effect switches) will be sent to the ground station user interface, as well as how the limit switches will stop the motors' movements when triggered. Figure 25 shows the corresponding legend to the flowchart.

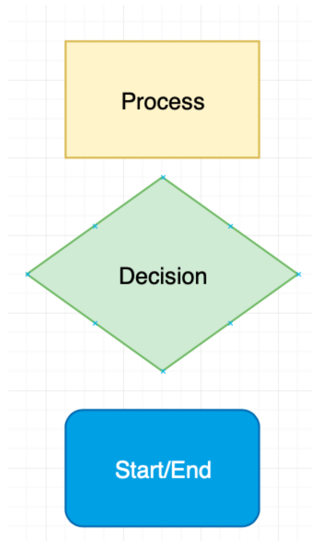


Figure 25: Limit Switch Flow Chart Legend

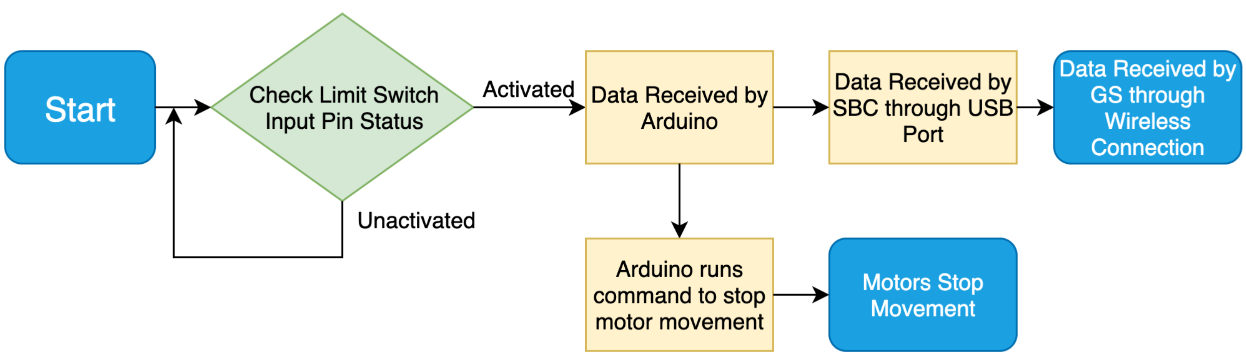


Figure 26: Limit Switch Flow Chart

The position of the limit switches, how their status is sent to the human operator, and how their status affects the motors, meets the following design requirements: "Non-Visual Confirmation the CSR is Secure", "Physical Limit Sensing", and "Limit Switches" (T2.2.3, T2.2.1, T3.2.1). The fulfilment of the latter design requirements allows the functional requirement "Avoidance of Damage" (T2.2) to be met. This is in relation to the critical project element of human interaction. They also help fulfill the functional requirement of "Data Handling" (T3.2).

The second type of position feedback is in the form of live video feed in conjunction with guidelines. There will be two cameras associated with ATLAS. One camera will be placed on the mother rover via a 3-D printed attachment. It will be placed with a 20° tilt towards the center of the mother rover. This camera will be located on the bottom plate of the mother rover on either the left or right sides. This will allow the human operator to watch the extension frame move outwards with and without the child scout rover. The camera will also have guidelines, shown below, that will help the human operator decide if the child scout rover is within the operational area, during the retrieval phase of the mission. During the deployment phase, the guidelines will help the human operator know when the wheels of the child scout rover are touching the ground. An example of this concept is also shown below. The second camera will be placed on the end effector back plate, pointing down towards the ground. The camera will also have guidelines, shown below, that will help the human operator guide the end effector into the child scout rover interface hole. The guidelines will also help the human operator with depth perception when actuating the vertical frame and end effector in a downward vertical motion. The camera guidelines will also help align the end effector to the child scout rover interface hole. The video itself will occur in real time and allow the human operator to react accordingly to the movement of ATLAS.

Figure 27 shows the simulated view from the end effector, along with an example of prototype guidelines. The figure below shows what the human operator would see if the end effector were correctly aligned with the child scout rover interface, and if the end effector were at the correct distance to start its actuation.

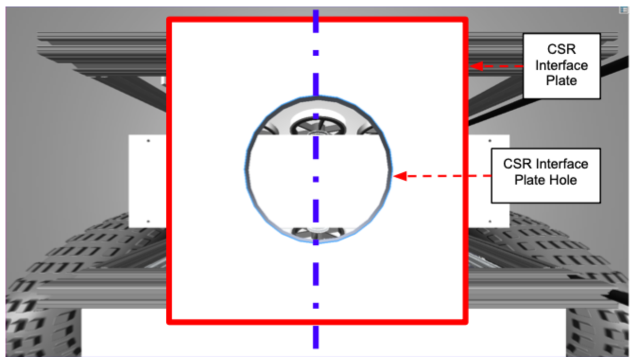


Figure 27: End Effector Video Guidelines: Aligned

Below, in Figure 28, the guidelines are offset. This is meant to convey the purpose of the guidelines. In the actual situation, the camera view would be turned, not the guidelines. The image below is simply to demonstrate the concept of guidelines. When image laid behind the guidelines appears larger, and you can see less, that means you are closer to your destination. Furthermore, the blue dotted line, if not aligned with the child scout rover interface, shows that the end effector is not rotated correctly.

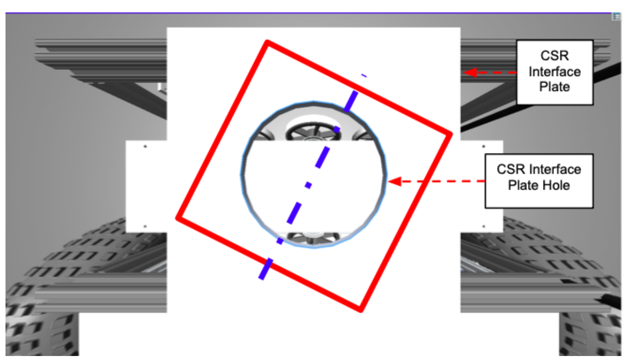


Figure 28: End Effector Video Guidelines: Not Aligned and Far Away from the CSR

Lastly, below is a guideline prototype of what the camera, located on the mother rover, will see. The green line represents the location where the child scout rover wheels are expected to make contact with the ground. The blue lines represent the vertical distances, while the red lines represent the horizontal distances.

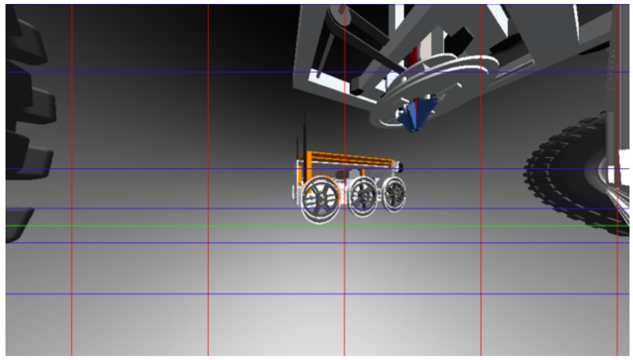


Figure 29: Mother Rover Video Guidelines: Operational Area and Wheel/Ground Contact

The preliminary code for the guidelines, using Python and OpenCV, can be found in the Appendix. The cameras used have the ability to change their settings in relation to the resolution, aspect ratio, and frames per second of the camera. For the design requirements, and the need to have real time video feed, the resolution of the camera will be set to 720p, or 1280 x 720 pixels. In order to achieve a field of view (FOV) of 120°, the aspect ratio of the window shown on the ground station will need to be 16:9. Lastly, the frames per second will be set to 30. Due to the latency, this may or may not be reached, however, the requirement is that only 20 frames per second are needed for the human operator to command ATLAS.

The live video cameras' specifications and locations, along with helpful guidelines, fulfill the design requirements of "CSCA Visual Data", "CSR Visual DATA", "Visual Data Resolution", "CSR Visual DATA FPS", "Ground Station Camera Guidelines", "Safe Deployment and Retrieval", and "Limit Switches" (T2.1.1, T2.1.2, T2.1.3, T2.1.4 , T3.1.4.5.2, T3.2.4.8, T3.2.1). Thus the functional requirements "Control of the CSCA", "Remote Control", and "Data Handling"(T2.1, T3.1, T3.2) are also met, in relation to the critical project element of human interaction.

e. Live Video Transmission & Display Live video transmission, in the form of two video cameras and relevant software, is necessary in order to fulfill the following functional requirements. These requirements relate to the ability of ATLAS to be commanded via a human operator, in real time. Furthermore, both cameras will be a huge part of how the human operator will command ATLAS. The commands for ATLAS must be made in real time. Therefore the cameras, in conjunction with how data is sent over the communication system, must be able to display video in real time.

The following design requirements meet the purpose of the functional requirements listed above. The way in which the design requirements are met will be discussed below, in the "Requirements Satisfaction" section.

The live video transmission requires two ELP megapixel Super Mini 720p USB Camera modules, which can be seen in Figure 21. Furthermore, the following software libraries will be used: OpenCV and FFmpeg. Protocols include UDP (User Datagram Protocol). Using the above, the live video feed is sent across the point to point network, and displayed on the ground station user interface.

The way in which video is transmitted to the ATLAS ground station is displayed in a high-level data flow chart below, Figure 31. The description below will strictly discuss the live video feed in relation to hardware. For communication related topics regarding live video feed, see section 7.2.1, part e.

The flowchart below focuses on how software sends the live video feed across the communication system. The camera output is compressed in the format of MJPEG. This format is not optional, and is linked to the camera itself. However, FFmepg library allows for converting the output format if needed. Then every frame is packetized and published to a socket address through UDP (User Datagram Protocol) using FFmpeg. On the ground station, a python script is subscribed to the socket address. OpenCV has the ability to decode the packet, and provide API (Application Programming Interface) for the Kivy library to display the video feed on the GUI. This is done with a latency of less than 300 ms, which is linked to a communication's design requirement, Visual Data (T4.1.4.1). Also, Figure 30 is the corresponding legend to the flowchart below.

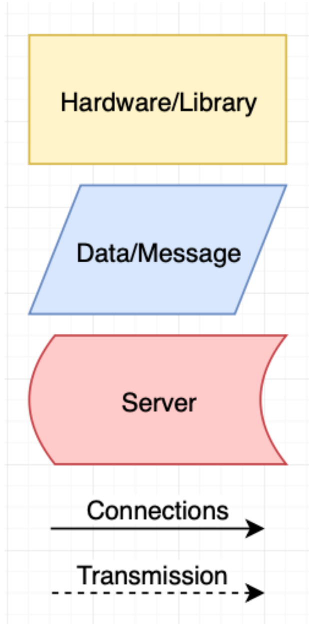


Figure 30: Video Transmission Flowchart Legend

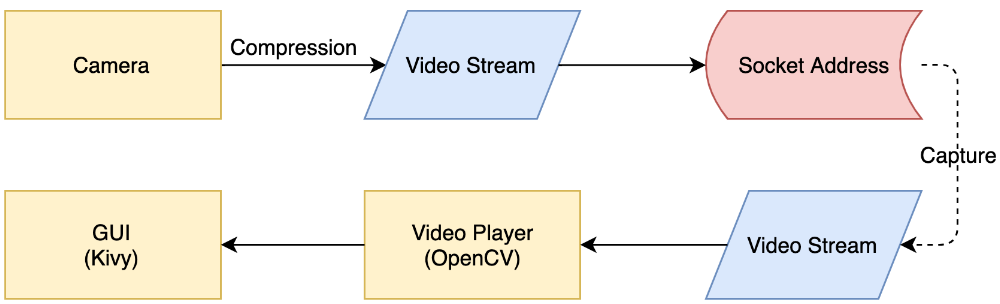


Figure 31: Video Transmission Data Flowchart

Figure 32 below shows a detailed flow diagram that explains the algorithms inside the client and server. The FFmpeg library is directly called using commands in the Tinkerboard's terminal. These commands are saved as system startups of the TinkerOS (operating system on the Tinkerboard). When the Tinkerboard is booted, the commands will have a delay to wait for the cameras to start operating. Then the video output will be compressed into a desired format, packetized and published to a socket address which is determined by the IP address of the Ethernet. In order to select the optimal format and codec, the team will need to conduct some testing on the hardware system. This is scheduled in the work plan section of this report. After the video stream has been published, the client on the ground station will subscribe to the same socket address. With a proper setting of the buffer size, OpenCV library has a built-in access to the API provided by FFmpeg. This allows for the client to identify the codec automatically and decode the video stream into a VideoCapture class. The frame data then can be read when needed.

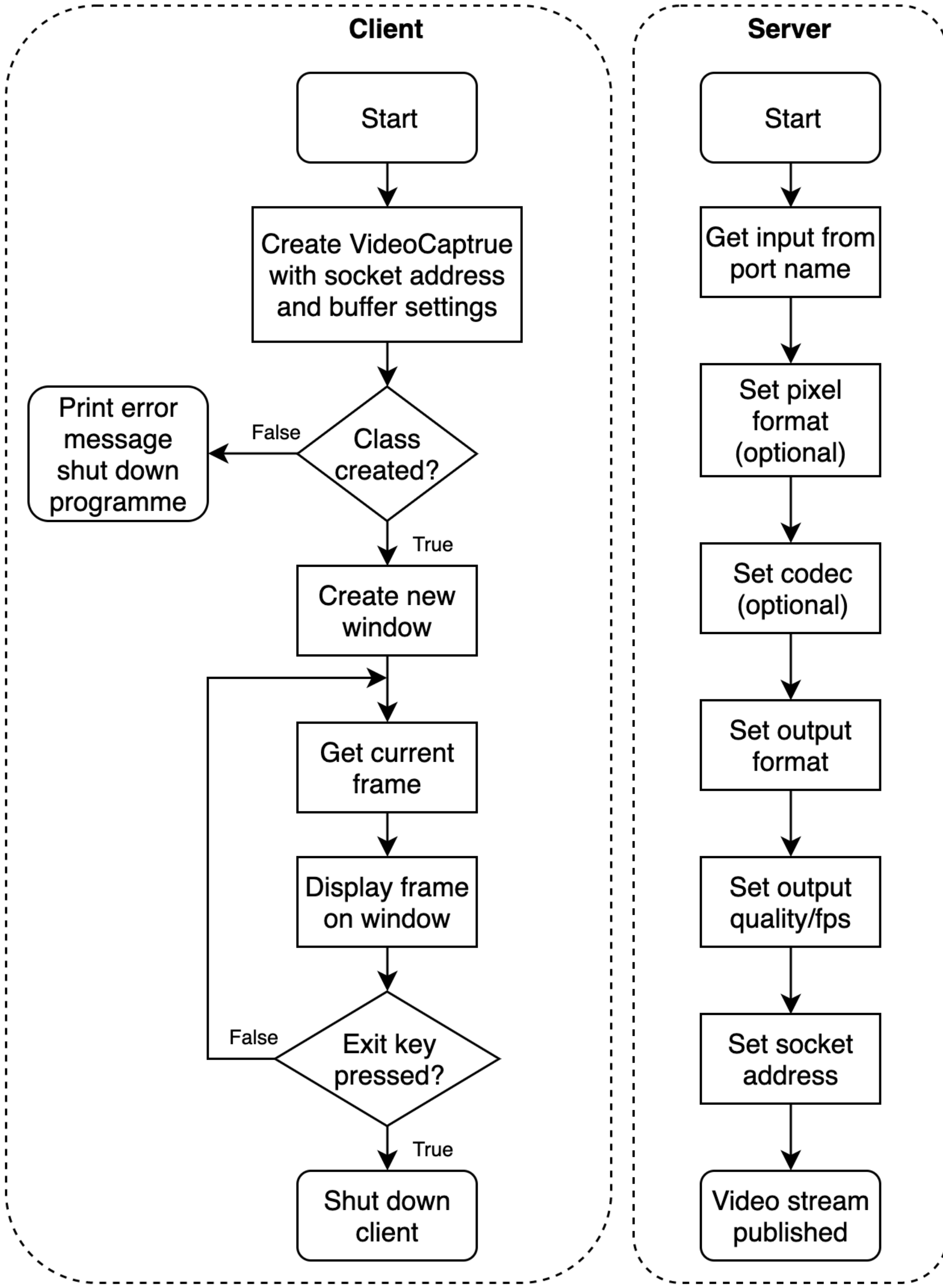


Figure 32: Video Transmission Flow Diagram

Overall, based on preliminary testing and the discussed flowcharts, the design requirements "Ground Station GUI" and GS Camera Display (T3.1.4 and T3.1.4.5) will be met. This will help fulfill the functional requirement of "Remote Control" (T3.1), in relation to human interaction.

f. Stepper Motor & Distances The stepper motors consist of four NEMA 23 motors to actuate the extension, transverse, and vertical frames, as well as the capture mechanism, while the NEMA 11 will be used to operate the rotary joint of the end effector. Instead of using encoders to ultimately determine the X,Y,and Z position of the end effector, step and direction commands sent to the stepper motors will be recorded and continuously updated. By keeping track of the number of step commands and the direction the step are to act in, the distance actuated in the X,Y, and Z direction can be directly calculated. The NEMA 23 stepper motors used for our project are non-captive

NEMA motors used in conjunction with a lead screw in order to actuate the extension, transverse, and vertical frames. Specification from the manufacturer states a resolution of 1e-6 meters of linear translation for each step of the stepper motor. This resolution is then used to convert steps commanded to the motor to distance traveled in the respective direction that a particular motor actuates in.

This distance calculation of course is heavily reliant on the assumption that each stepper motor will not skip steps, for each skipped step results in error in the calculated vs actual position of the end effector. This assumption is considered valid as the environment designed for the motors to operate in will not approach the boundary of the maximum force output of the motor, will supply the motors with adequate voltage and current, and the motors do not have stated speed requirements, all of which are the primary causes for skipped steps.

The calculated and displayed position data is primarily useful to the user after the CSR has been captured. Before retrieval, the position data serves little purpose to the user, as they will not know the position of the CSR relative to the end effector. However, once the CSR has been captured by the end effector, the fixed geometry of the CSR and ATLAS allow the user to know where the CSR is relative to various aspects of ATLAS, such as limits of the frame, the "tusks" that hold the CSR once it has been captured, and other parts of the frame. Known position data will help the user avoid damaging both the CSR and ATLAS while transitioning from capture to dock of the CSR.

Not only is position data useful for the dock procedure, it is also used for a level of redundancy when capturing the CSR as well. While visual data is the primary data used to capture the CSR, position data will confirm the rough position of the end effector relative to the CSR, although not well enough to capture it without any visual input.

The required components for both actuation and distance calculation include the 5 afore mentioned NEMA stepper motors, any necessary lead screws, and a microcontroller, specifically in this case an Arduino Due. The step count to linear translation conversion is done within the Arduino for every loop it executes.

The control of each stepper motor and determination of joint and end effector position directly relates to requirements T3.1.3, T3.1.4, and T2.1.5, which detail the need for numerical data relating to the change position of the motors, and the ability for ATLAS to be remotely controlled by the operator to deploy, retrieve, and store the CSR. By implementing the ability to calculate the linear translation of the end effector in the X,Y, and Z direction by counting commanded steps to each stepper motor, the previously stated three requirements are satisfied.

Figure 33 below illustrates the basic algorithm that the stepper motors will use in order to actuate the extension, transverse, and vertical frame movement along with end effector rotation and capture motion.

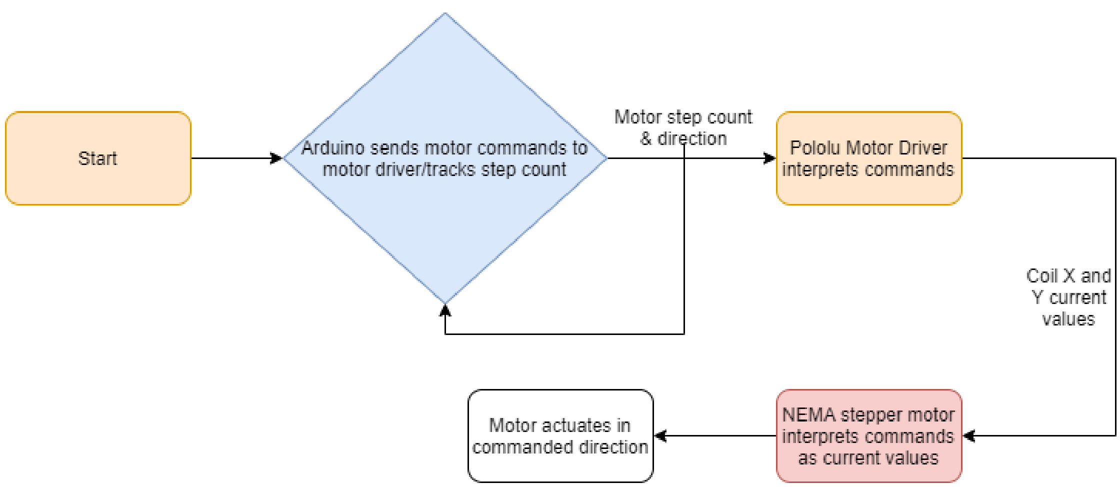


Figure 33: Basic Stepper Motor Control Algorithm

6. Manufacturing

6.1. Mechanical

Authors: Clara Bader, Jamison Bunnell

6.1.1. Manufacturing Scope

All of the custom components for the ATLAS project were manufactured in the Aerospace machine shop by members of the team. Many of these parts were quite complex, so they required the use of lathes, CNCs, milling machines, and other tools. When possible hardware components were ordered that required minimal machining as this assisted in expediting the manufacturing process. Despite this, the manufacturing aspect was a large undertaking since it was such a hardware-intensive project. All hardware components required some machining excluding the transverse frame support rods, bearings, nuts, and bolts.

a. Extension Frame

Component	Equipment	Description	Status
Extension Beams	Band Saw, Mill	Cut to size with Band Saw. Support holes drilled on Mill	Not Completed
NEMA 23 Lead Screw	Lathes	Ends milled down to 1/4 in. Die to thread ends.	Not Completed
Mother Rover supports	Mill	Mounting holes drilled on Mill	Started
Guide Rail Mount Plate	Mill	Mounting holes milled into plate	Not Completed
Guide Rails	Mill	Mounting holes milled	Not Completed
Extension Cross Supports	Mill	Mill mounting holes.	Not Completed
Roller Assembly	Welding, Mill	Weld steel assembly. Mill roller mounting holes.	Started
Motor Mount	Welding, Mill	Weld steel together, Mill mounting and motor holes.	Not Completed
Mother Rover Top Plate	Mill	Cut outs for supports milled into MR top plate.	Not Completed

Figure 34: Extension Frame Manufacturing

b. Vertical Frame and End Effector

Component	Equipment	Description	Status
Vertical Support Rods	Lathes, Band Saw	1/2 in Al rods cut down to size on band saw, finishing pass on lathe, lathed ends to 1/4 in. Die to thread ends.	Completed
NEMA 23 Lead Screw	Lathes, Band Saw	Cut to size on band saw, lathed ends to 1/4 in. Die to thread ends.	Completed
Vertical Load Plate	CNC	Face plate and CNC holes	Completed
Transvers Motor Mount	CNC	Holes for screws and motor into steel L bracket	Completed
Vertical Support Plate	CNC	Face, cut square plate & 1/4 in holes for vertical supports and lead screw	Completed
End Effector Hub	CNC	Al block faced and CNC'd down to size	Completed
Petals	CNC, Band Saw	Al plate faced and petal shapes CNC'd. Petals cut out of plate with band saw.	Completed
Linkages	CNC	Al plate faced and linkages CNC'd. Linkages cut out of plate with band saw.	Completed
End Effector Back Plate	CNC	Al plate faced. Outline and holes cut with CNC	Completed

Figure 35: Vertical Frame and End Effector Manufacturing

6.1.2. Manufacturing Outcome

As shown in the above tables, all of the manufactured parts were completed except for the extension frame components. Per the manufacturing schedule, the end effector was completed first followed by the vertical and transverse frames. The resultant completed components came out better than expected, as we were able to powder-coat many of the parts to improve the visual appeal of the project.

Many of the challenges faced during the manufacturing process related to the complexity of some of the components and the need for high levels of precision. The complex assemblies often required tight tolerances, elseways the parts would not fit together and a new part would need to be made. To overcome this challenge, milling machines were used to define the rough dimensions of a part, then an automated CNC machine was programmed to cut the necessary elements of a part to tight tolerances. This allowed the parts to be made much more precisely and quickly, with less worry about ruining the component.

6.1.3. Component Integration

Component integration began with the end effector and vertical frame, as these assemblies were completed excluding the installation of the NEMA motors. Pictures of this assembly can be seen in Figures 36 and 37 below.

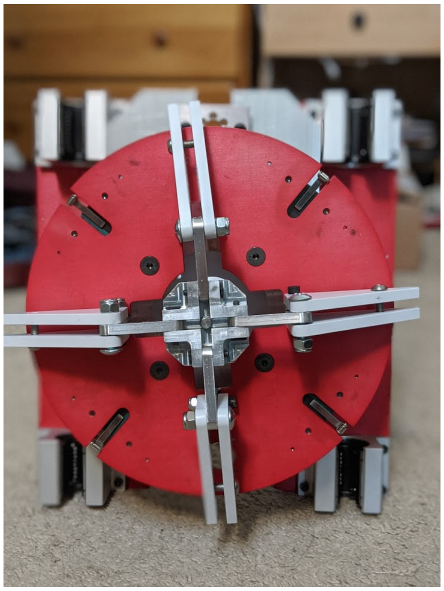


Figure 36: Completed End Effector End View

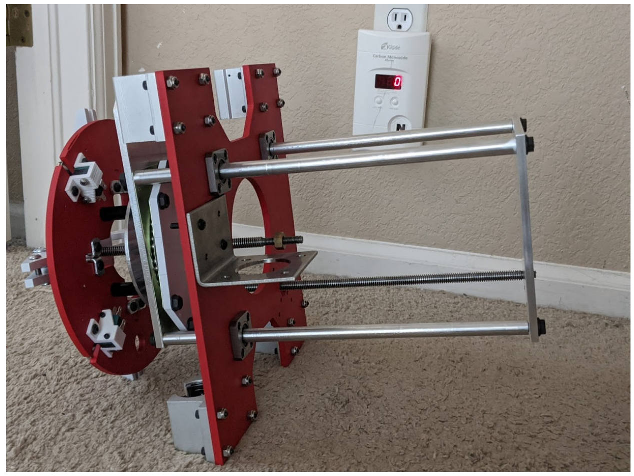


Figure 37: Completed End Effector Side View

After the completion of the extension frame the end effector, vertical frame, and transverse frame would have been integrated onto the mother rover as shown in Figure 8.

6.2. Electronics

Authors: Sage Herrin, Wyatt George

6.2.1. Manufacturing Scope

The electronic components of the project consisted of an ASUS Tinkerboard SBC, an Arduino Due Microcontroller, 5 NEMA 23 motors, 1 NEMA 11 motor, limit switches and hall effect sensors, and wiring necessary to connect all peripheral components to the microcontroller and SBC. All components were purchased as COTS and in the process of being implemented in the system before manufacturing ceased. The overall functionality of of the electronics subsystem was to facilitate and coordinate all movement of ATLAS in the process of deploying and retrieving the CSR.

6.2.2. Manufacturing Outcome

None of the electrical components used on the system were manufactured by the team, as all were purchased from various suppliers. All components had been acquired at the time the team was forced to cease all work in the project, and was in the process of integrating components into the system to complete a working system capable of controlling the dynamics aspects of ATLAS. This includes controlling the motion of the extension frame, the transverse frame, the vertical frame, and the end effector.

6.2.3. Component Integration

The motor drivers were successfully integrated with at least one motor, and the motor was successfully run. Furthermore, the Arduino and the Tinkerboard were integrated to the point that they were able to send and receive data to each other during component testing. Limit switch and hall effect sensor capabilities were verified when both were integrated into the system and were confirmed to effectively stop motor motion when triggered.

6.3. Software

Authors: Emily Wiedenfeller, Jason Leng

6.3.1. Manufacturing Scope

All the software libraries used for the project were either open-source or free. The ground station GUI was developed using Python Kivy and Python Socket. The video transmission was implemented using Python, OpenCV, and FFMpeg. An Arduino stepper motor control library was used to drive motors.

6.3.2. Manufacturing Outcome

By the time that the manufacturing was stopped, a test version of the ground station GUI was developed. It was capable of displaying both videos with guidelines on them. The GUI also had the functionality to show the limit switch status. However, the position of the CSR had not been animated yet. One of the challenges in developing the GUI was the mismatch of versions between Python and Kivy. Python 3.8 was originally selected to be the version for GUI development. However, it was not documented on Kivy's website that the newest version of Kivy did not support Python 3.8. To resolve the issue, the team made a decision to downgrade the Python version to 3.7. The conversion of the environment was seen as unexpected development time. For software that runs on the SBC, the SBC was able to transmit video output of both cameras wirelessly to the ground station. The UDP protocol was considered to have a lower latency but harder to organize the frames. The team spent most time working on configuring the setup in order to provide stable video feed on the ground station GUI. The team also implemented motor control using the Arduino and the serial communication between the Arduino and the SBC.

6.3.3. Component Integration

To send and receive data between software components, TCP and UDP protocols were used to communicate wirelessly. The TCP focused on passing commands and position data without losing significant amount of packets. And the UDP was mainly for transmitting video at low latency. The FFMpeg library allows the SBC for compressing video with several codecs. MJPEG format was selected based on the bandwidth and video quality. For the interface between the SBC and the MCU, USB serial port was used together with Python Serial and the built-in serial function of the Arduino. The commands were defined as characters. And the position data was formatted into a string which contains the 3-D position of the arm and the limit switch status.

7. Verification and Validation

Authors: Emily Weidenfeller, Miriam Rosenshein, Charles MacCraiger, Jason Leng

7.1. Test Plan

Table 4: Major Tests Schedule

Test	Date	Location	Level of Success	Driving Requirements
Hardware-Deployment	4/2/20	CU Boulder Aerospace Building	Structure 4	T1.2
Hardware-Retrieval	4/7/20	CU Boulder Aerospace Building	Structure 4	T1.3
Hardware-Carry	4/10/20	CU Boulder Aerospace Building	Structure 4	T1.1
Sensing-Component Testing	3/7/20	CU Boulder Aerospace Building	Sensing 4	T2.1, T2.2
Communication-Two Way Communication	2/1/20	Bear Creek Field and & South Campus Field	Communication 4	T4.1
C&DH-System Testing	4/7/20	CU Boulder Aerospace Building	Control 4	T3.1, T3.2

7.2. Hardware - Deployment

7.2.1. Objective: Requirement Verification and Project Success Criteria

This test would have verified that ATLAS is able to meet the level 4 structural success criteria of deploying the CSR. Deployment is defined as completing the sequence of unhooking the CSR, extending the arm, lowering the CSR, end effector is closed, end effector retreats. This test would have verified requirements T1.2, T1.2.1, and T1.2.1.1.

7.2.2. Test Plan

The order of operations for this test is shown in Figure 38. This test would have been done after ATLAS had been mounted onto the mother rover. It would have been completed at the CU Boulder Aerospace Building. The testing would have been preformed both inside in the senior projects room, and outside on grass to simulate a more realistic mission environment. Outside testing would only have been done on fair weather days that meet the environmental requirements. First, the team would have verify that all systems are operating as expected by maneuvering the dynamic mechanisms and checking the status of sensors. Once the starting checklist had been completed the team may move on to completing deployment testing. Using a level the team will verify that the mother rover was within 5° of the plane of the horizon. Then the team would have began the deployment sequence without the CSR.

The first set of testing would have occurred inside the senior projects room without the CSR attached. The sequence of operation is as described in the objective. The team would have begun raising the end effector enough for the CSR to move past the hooks that would be holding it during motion. Then the arm would extend out to half of it's full range of extension, about 20". The team would have visually verified using onboard cameras that there are no obstructions or dips in the ground that would interfere with deployment. The arm would have then been lowered until the height of the CSR is left between the end effector and the ground. This distance will be verified using motor step assessments and a limit switch in the vertical frame. Once in position, the end effector would have retracted its petals to fully stowed positions. Finally the vertical frame would have retracted up with the end effector.

This test would have been completed several times without the CSR to ensure safety. After the sequence had been completed inside with the CSR several times the whole procedure will be done outside in grass. First without the CSR and then with it.

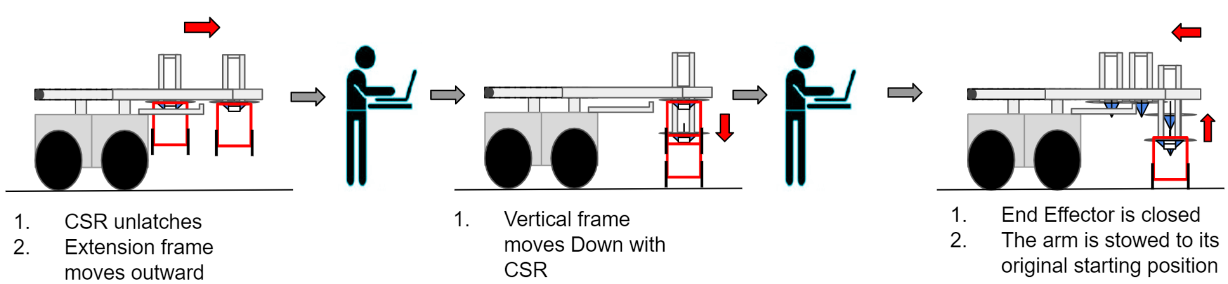


Figure 38: Deployment Testing Order of Operations

This test would have been considered a failure if ATLAS was unable to complete any phase of the deployment process with or without the CSR.

7.2.3. Required Equipment and Measurements

The requirement for this test was full system integration. ATLAS must have been attached to the mother rover, the CSR must have had the revised interface plate installed, and software/controls must have been fully implemented. Communications did not need to be installed as this can be done while tethered to the ground station. An accelerometer may have been placed on the CSR to ensure that the motor limiters were sufficiently controlling the speed during this test. Additionally the team would have visually recorded the actions of ATLAS from the side for further analysis. Risks of damaging the CSR would have been mitigated by having a secondary rope system holding the CSR in the event of dropping.

7.3. Hardware - Retrieval

7.3.1. Objective: Requirement Verification and Project Success Criteria

This test is very similar to the deployment test. It would have verified that ATLAS is able to meet the level 4 structural success criteria of retrieving the CSR. Deployment is defined as completing the sequence of the arm unstowing, the arm extends, the end effector goes down, then the end effector opens, the plate clamps down, and the end effector goes up. This test would have verified requirements T1.3, T1.3.1, T1.3.1.1, T1.3.1.3, and T1.3.2.

7.3.2. Test Plan

The order of operations for this test is shown in Figure 39. This test would have been done after ATLAS has been mounted onto the mother rover. It would have been completed at the CU Boulder Aerospace Building. The testing would have been preformed both inside in the senior projects room, and outside on grass to simulate a more realistic mission environment. Outside testing will only be done on fair weather days that meet the environmental requirements. First, the team would have verified that all systems were operating as expected by maneuvering the dynamic mechanisms and checking the status of sensors. Once the starting checklist had been completed the team would have moved on to completing deployment testing. Using a level the team would have verified that the mother rover is within 5° of the plane of the horizon. Then the team would have began the deployment sequence without the CSR.

The first set of testing would have occurred inside the senior projects room without the CSR attached. The sequence of operation is as described in the objective. The team would have began unstowing the arm from it's position on the MR. It would have then been extended out to the location of the CSR via commands from the operator. The vertical frame would have been lowered with the end effector. Once in position, the end effector petals would have opened and the plate would have clamped down as if the CSR were in position. Once visually confirmed to be fully actuated, the end effector would have been raised using the vertical frame. The extension frame would have then been retracted. The vertical frame would have lifted the end effector such that it may clear the hooks used during the traversal phase to hold the CSR. It would have then been lowered into the docked position.

This test would have been completed several times without the CSR to ensure safety. After the sequence had been completed inside with the CSR several times the whole procedure will be done outside in grass. First without the CSR and then with it.

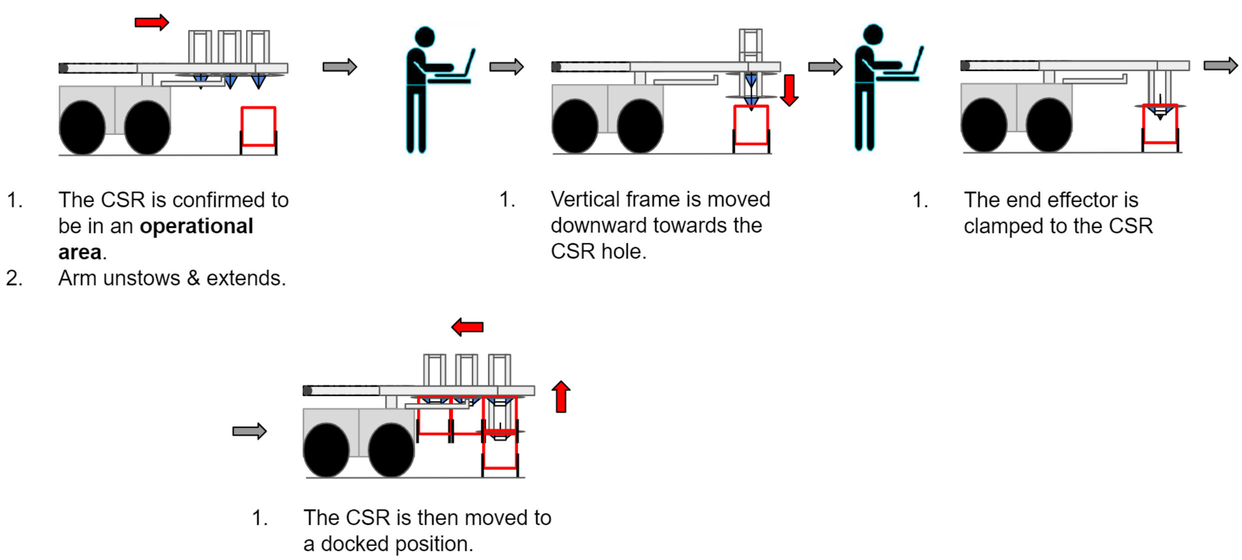


Figure 39: Retrieval Testing Order of Operations

This test would have been considered a failure if ATLAS was unable to complete any phase of the retrieval process with or without the CSR.

7.3.3. Required Equipment and Measurements

The requirement for this test was full system integration. ATLAS must have been attached to the mother rover, the CSR must have had the revised interface plate installed, and software/controls must have been fully implemented. Communications did not need to be installed as this can be done while tethered to the ground station. An accelerometer may have been placed on the CSR to ensure that the motor limiters were sufficiently controlling the speed during this test. Additionally the team would have visually recorded the actions of ATLAS from the side for further analysis. Risks of damaging the CSR would have been mitigated by having a secondary rope system holding the CSR in the event of dropping.

7.4. Hardware - Carry

7.4.1. Objective: Requirement Verification and Project Success Criteria

This test would have verified that ATLAS was able to meet the level 4 structural success criteria of carry the CSR on planes between $-20°$ and $+20°$. The carrying phase of the mission is that where the CSR is docked on the mother rover and it is traversing across terrain defined by the mission. This test would have verified requirements T1.1, T1.1.1, T1.1.1.1, T1.1.1.2, T1.1.1.3, T1.1.1.4, T1.1.2, T1.1.3, T1.1.4, and T1.1.5.

7.4.2. Test Plan

This test would have been done on the Boulder Creek Path near the CU Boulder Main Campus or an equivalent location closer to the CU Boulder Aerospace Building. The test phases that would have been completed for this test are shown in Figure 40. The mother rover would have carried the CSR up and down a 20° slope and measured the vibration of the CSR via an accelerometer. Additionally the test would have been done while traversing a 5" obstacle. The team would have also visually recorded the excursion.

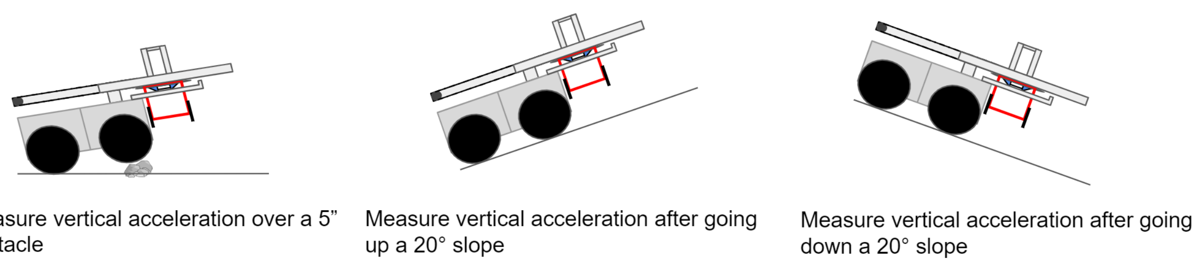


Figure 40: Carrying Test Scenarios

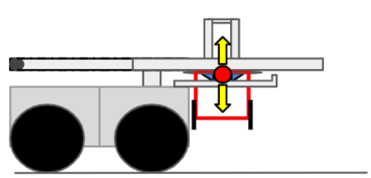


Figure 41: How Vibration Test Data Will Be Captured

This test is considered a failure if ATLAS is unable to complete any of the carrying criteria.

7.4.3. Required Equipment and Measurements

The requirement for this test was full system integration. ATLAS must have been attached to the mother rover, the CSR must have had the revised interface plate installed, two way communication must have been functional and software/controls must be fully implemented. The team would have visually recorded the actions of ATLAS from the side for further analysis as well as affixing an accelerometer to the CSR to measure vibration. A risk of this test is that the mother rover may tip if the slope attempted is too high. To mitigate this the team would have carefully measure each slope before attempting traversal.

7.5. Sensing - Integrated Component Testing

7.5.1. Objective: Requirement Verification and Project Success Criteria

The purpose of this test was to verify that each sensing component would satisfy the requirements set by the mission. ATLAS has two ELP megapixel Super Mini 720p USB Cameras as well as nine limit switches and two hall effect sensors. The camera components are used to provide visual data of the end effector from the view of the mother rover, and looking down on the end effector from the above on the transverse frame. The limit switches are being installed to ensure no frame extends so far as to cause damage to ATLAS, the mother rover, or the CSR. These have been chosen to satisfy the requirements T2.1, T2.1.1, T2.1.2, T2.1.3, T2.1.4, T2.2, T2.2.1, and T2.2.3.

7.5.2. Test Plan

These component tests took place at the CU Boulder Aerospace Building. The team verified that the camera was capturing at a resolution of at least 720p with a FOV of at least 100° for both the horizontal and vertical cameras. The results are shown in Table tab:sensetest. The location of the cameras and limit switches is shown in Figure 42.

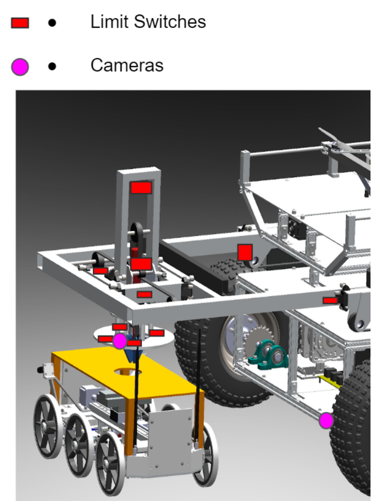


Figure 42: Camera and Limit Switch Locations for Resolution Testing and Limit Switch Testing

The team would have also verified the functionality of the limit switches. This would have been done by running each frame to its full extension and also verify that limit switches had been triggered appropriately. The stopping of movement of the motors would have been recorded via video. The two hall effect sensors would have also acted as limit switches for the rotary joint. They would have ensured that the end effector is not rotated so far in any direction that it causes damages to the mechanisms. This would have been recorded via video as well.

7.5.3. Results

These are the test results for the video sensor test. The results highlighted in green met our requirements. Thus the team chose to stream video with a configuration of 15 FPS at 360p.

Table 5: Video Sensor Test Results

Frame Rate	30 FPS	30 FPS	15 FPS	15 FPS
Resolution	720p	360p	720p	360p
Latency	>1000ms	>1000 ms	>500 ms	<500 ms

7.6. Communication - Two Way Communication

7.6.1. Objective: Requirement Verification and Project Success Criteria

The functional requirement, T4.1 ATLAS Two Way Communication, states that ATLAS shall engage in two way radio communication with the ground station. The objective of the following test was to verify the ATLAS communication system's ability to transmit video and data through 250 meters of trees as specified in the mission environment. By completing a successful test, the functional requirement mentioned above would have been met. The success criteria for this test include the following: ability to send commands, data, and live video feed in the defined mission environment, as well as recording a signal strength that can handle the environment attenuation and closely matches the model seen in Figure 43.

7.6.2. Test Plan

To start the test, the signal strength from the Ubiquiti Console (Ubiquiti Rocket M900) was be recorded when standing directly next to the ground station. Then the tester moved 5 meters, incrementally, recording the signal strength in dB, video latency in ms, data rate in kbps, and qualitative video quality each time. This process will be repeated up until 260 meters. The test occurred at the Aerospace Building with no vegetation. It would have been repeated at another location with vegetation if the team had been able to continue testing.

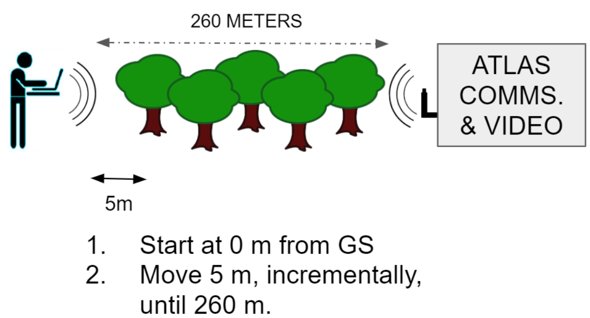


Figure 43: Communication Two Way Communication Testing

7.6.3. Results

The results of the two-way communication testing is shown below. The team was unable to finish the test and collect data with vegetation. Additionally the team collected some bad data and needed to redo the signal strength and video latency portion of the test.

Table 6: Two way communication test. 250 meters no vegetation

	No Vegetation			Vegetation		
	Requirement	Expected	Result	Requirement	Expected	Result
Signal Strength	>8 dB Margin	>8 dB Margin	New Data needed	>8 dB Margin	>8 dB Margin	
Video Latency	<500 ms	<300 ms	New Data needed	<500 ms	<500 ms	
Command Latency	<500 ms	<300 ms	11.6 ± 16.5 ms	<500 ms	<500 ms	
Maximum Data Rate	<6 Mbps	<6 Mbps	2.74 ± 0.32 Mbps	<6 Mbps	<6 Mbps	

This test validated the levels of success to level two: ”The ground station communicates 250 meters away from ATLAS with 0 trees per acre”. It also partially validated requirement T4.1: ”ATLAS Two Way Communication, states that ATLAS shall engage in two way radio communication with the ground station”.

7.7. C&DH - System Testing

7.7.1. Objective: Requirement Verification and Project Success Criteria

The objective of C&DH System testing was to do a final integrated verification test of ATLAS. This test would have verified requirements T3.1 and T3.2. By completing this test successfully the team would have ensured adequate control of ATLAS as well as having met the teams requirements for data handling. ATLAS must be able to maintain joint position while performing other tasks, dock/undock and deploy/retrieve the CSR via remote command. ATLAS must stow its arm via command from the ground station. ATLAS also must update the limit switch status and provide position data with an error less than 1 inch.

7.7.2. Test Plan

This test plan would have taken place at the CU Boulder Aerospace Building. It would have been used to test all functionality described in ATLASs requirements at a close range. First the team would have gone through the startup process, verifying at each stage that all systems are functional and ready to proceed safely. Upon completion of startup procedures the test would have begun. Additionally, this test might have been performed several times on a test fixture mimicking the MR before it is tested with full integration. Both iterations of this test have the same procedure.

The team would have remotely commanded ATLAS from the ground station to move in all three axes to each limit switch. The team would have used this to verify joint station keeping and the ability to stow the arm without the CSR. Next the team would have placed the CSR within the operational zone and used the ground station and overlaid lines on the visual data to interface appropriately with the CSR. Next the team would have lifted and docked the CSR on hooks. At each stage the team would have verified that all limit switch and positional outputs are maintaining accuracy of ±1” from real values. The team would have then undocked the CSR, again paying close attention to the GUI output. The testing would have been recorded via video camera. GUI output would have also been saved for later comparison to visual data. The GUI and the distance test would have been done as seen in Figure 44.

After the tests for system functionalities were done, the team would have performed tests at incremental distances to test the stability and latency of the system. The team also wanted to test for the maximum range ATLAS can operate while maintaining full functionalities to ensure the capability and acceptable tolerance of the C&DH system.

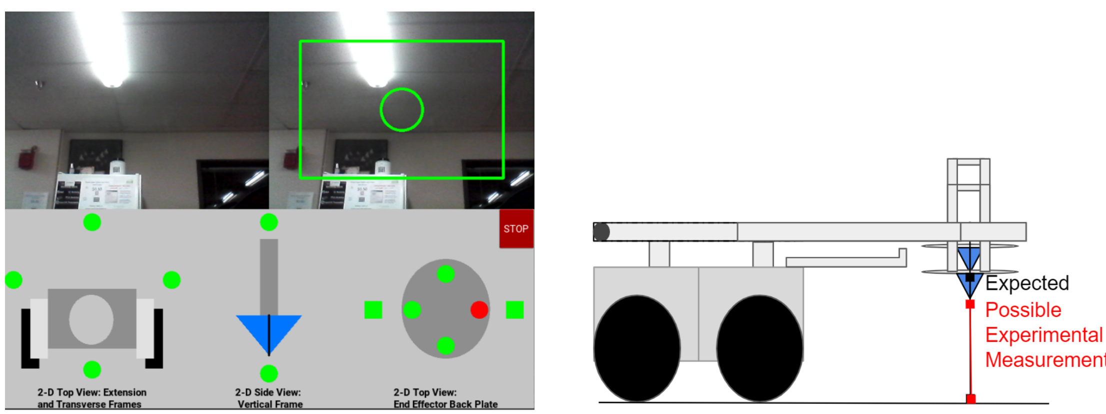


Figure 44: C&DH testing

7.7.3. Required Equipment and Measurements

The required equipment for this test was a standard measuring stick with accuracy of 1/32”. This would have been more than sufficient to ensure that the location of the end effector is as expected within ±1”. Additionally the team would have required a video camera for recording the movement of ATLAS. This can by done using a cellular phone or designated recording device. Finally ALTAS must have been fully assembled and able to receive remote commands at the time this test was preformed for the second phase of this test. The CSR must have had its new interface plate installed for both parts.

8. Risk Assessment and Mitigation

Authors: Kelan Crespin

Project risk identification began by analyzing the points of possible failure, this includes software interfaces, hardware interfaces and P.A.B. expert concerns. Each sub-team regularly visited expert advisors regarding specific design choices, project planning, and simulation/modeling of project elements. All of these concerns were compiled into a risk table, of which several were finalized and ranked as most severe. These risks were dealt with the most promptly in order to ensure project success and that possible failure modes did not carry forward though to any further designs.

Each identified risk was categorized into two overarching categories: technical risks, and non-technical risks. Technical risks are the risks specific to hardware or electronic components of the project. While non-technical risks encompass those risks that relate to administrative concerns or team hazards.

For the technical risks, each concern will be discussed in terms of the effected sub-team. For the Hardware and Manufacturing team, the most significant risks are specific to designed interfaces. As a primary example, the method that ATLAS is going to be actuated along the extension frame includes a custom designed and manufactured roller/guide-rail assembly. This assembly fixes a previous design while also increasing the complexity of implementation. The driving risk for this interface is that the design calls for a single lead-screw driving motor which is planned to be mounted on one side of the Mother Rover. This will create a moment that could cause binding in the extension frame as the driven side of the extension frame is actuated and the non-driven side lags behind. Tolerances are such that this uneven actuation could cause the rollers and the guide-rail assembly to seize up and fail to extend. The mitigation strategy for this is being implemented in the form of design modification and the fact that the team has excess funds left over to deal with this concern is a testament to the efficacy of the risk driven design method utilized by the team. The electronics sub-team is primarily concerned with the powering the embedded systems. This includes the three batteries used in the design and the Arduino DUE which is used to the power the POLOLU MC33926 Motor Driver Carriers, NEMA 23 and NEMA 11 motors. For these subsystems the driving concern leading into the Spring 2020 semester are over drawing current (technical), and motor driver heating (non-technical - will be discussed in the non-technical section). The current is a concern because the there exists the possibility of overdrawing current into the drivers and ruining them. There are fuses in the design so that over overdrawing can ruin the fuses but saves more important components. The problem being that if a fuse is tripped during the execution of the mission, a motor will fail to actuate. This means that although the fuse removes the possibility of ruining the expensive components of the system, if the fuses trip too easily, ATLAS can become nonfunctional. The efficacy of the fuses determines the reliability of the power subsystem to continuously power ATLAS. Fuse failure is unfortunately likely, however, the inexpensive nature of fuses does not mean that a fuse failure will result in a critical project failure.

The non-technical risks are those which have either administrative (financial, scheduling, logistical) or may result in some specific hazard to persons on the team. The most driving financial concern is that the hardware team is limited by the budget, the design would be best served with two simultaneously driven motors on the extension frame. However, the limited budget has made it necessary to design the system with only one such motor. This initial budgetary shortage means that although the system will work, a single motor will require some hardware designed methods for mitigating failure modes brought on by uneven motor actuation. Additionally, there are is also the concern for scheduling. The spring semester is densely scheduled, and finding the time to get all the necessary team members qualified to be able to use the workshops and tools for manufacturing the parts for ATLAS may be difficult. This is because there are several other hardware intensive projects which will require the use of similar tools and machines in their own assembly process. The collective need to use these facilities will make access a commodity. This will require effective scheduling and disciplined preparation so that time using these facilities is not wasted.

Team hazards are the final category of non-technical risks that will need to be dealt with in order to ensure that all persons are safe. The current motor driver selection is going to be a cause of one such risk. The small drivers will carry a significant current load given their size. Although the drivers will not be operating at the maximum current capacity specifications, these parts are likely to get hot enough to burn someone if they come in direct contact with the boards. The design calls for a housing that will shield any persons for direct contact during normal operation, however, the concern is when these elements are being integrated and tested. During this phase of manufacture, the drivers will likely be attached to a prototyping/impermanent assembly and it is during this exposed time that injury is possible. There will be safety procedures in place to mitigate the risk of persons being burnt during the testing and assembly phase.

Risk Title	Description	Severity	Likelihood	Rank
Extension Frame (Technical)	The single motor design of the extension frame may suffer from binding due to the asymmetric force applied	Intolerable	Improbable	High
Current Overdraw (Technical)	The current over draw and fuse failure result in inability to actuate the motors	Tolerable	Possible	Medium
Scheduling (Non-technical)	Availability of manufacturing spaces will be limited in the Spring of 2020	Acceptable	Probable	Medium
Team Hazard (Non-technical)	The heating of the motor driver carries could cause burns if handled improperly	Undesirable	Improbable	Medium

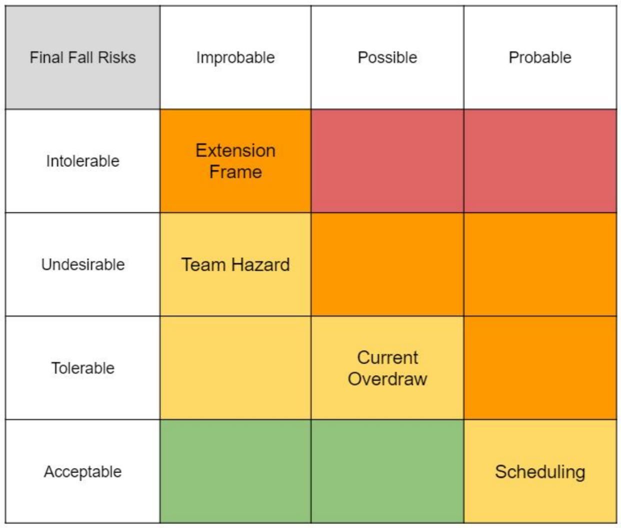


Figure 45: Risk Matrix

The highest priority failure mode of the system is currently that the extension frame could bind up as there is currently only one motor in the design mounted on one extreme side. This risk is solvable as there are leftover funds in the project budget to include a second motor which would effectively remove the concern. Although the addition of the second motor would fix the binding issue, it effect other sub-systems in ATLAS. The second motor would need to be actuated in unison with first motor. The actuation of these motors in unison adds to the software complexity such that there will need to be considerable time and effort afforded to the software implementation of sufficiently simultaneous motor actuation. The problem being that the SPI enabled motor drivers will need to be activated in sequence as the the protocol for SPI is strictly sequential and bound to a single peripheral at a given time. This will require that the commands for these two motors in particular be activated consecutively and rapidly. The time to activate each of these motors will be dependant on the timing of the stepper motor command signal. As PWM (pulse with modulation) waves are generally on the order of milliseconds, and the clock speed of the Arduino DUE is on the order of Megahertz, the hardware is certainly capable of executing the commands necessary to simultaneously drive the motors. The software must be timed such that command signals are sent to the motor drivers quickly enough that they effectively receive simultaneous commands. Two members on the team have embedded systems experience, and have worked with timing control signals in course work. With this skill-set, the binding of the extension frame can be solved given either a single or duel motor design. Although, the binding of the extension frame is a driving concern moving into the Spring 2020 semester, this is a problem that is solvable given the time, financial, and logistical constraints of the project.

Changing the design of the extension frame to include dual motors will increase the reliability of ATLAS however this will need to be weighed against the drawbacks of complicating the software which is arguably the most difficult aspect of the project. While maintaining the current single motor design does not decrease capability, it is more likely to suffer from mechanical complications which are possible to remove with modifications to the hardware of the roller/guide-rail assemblies.

As an important note, the ATLAS financial lead successfully petitioned the Engineering Excellence fund for additional funding. With the additional budget the dual motor design is most likely to be implemented as there is not a much larger margin for financial

9. Project Planning

Authors: Emily Weidenfeller, Colton Kalbacher

9.1. Organizational chart

Below, in Figure 46, is the team's organizational chart. The team decided to partially adopt an AGILE leadership structure. The AGILE structure introduces the product owner and scrum master. The product owner connects the customer and advisor to the team. It is the product owner's job to make sure that the team is completing the right work. In other words, is the team building what the customer asked for? The scrum master's job is to make sure the team stays on task and to make sure any obstacles to the team are removed. In regards to the system engineer, it is their job to make sure the sub-teams are communicating. The systems engineering position is more technically focused.

The main contributors of the project are shown in gray. The general team leads are shown in orange. Lastly, red represents the hardware subteam, yellow represents the electronics subteam, and blue represents the software subteam. All three subteams have their own leads. These are the subteam leads. Then within the subteams, are the more specific and technically focused leads.

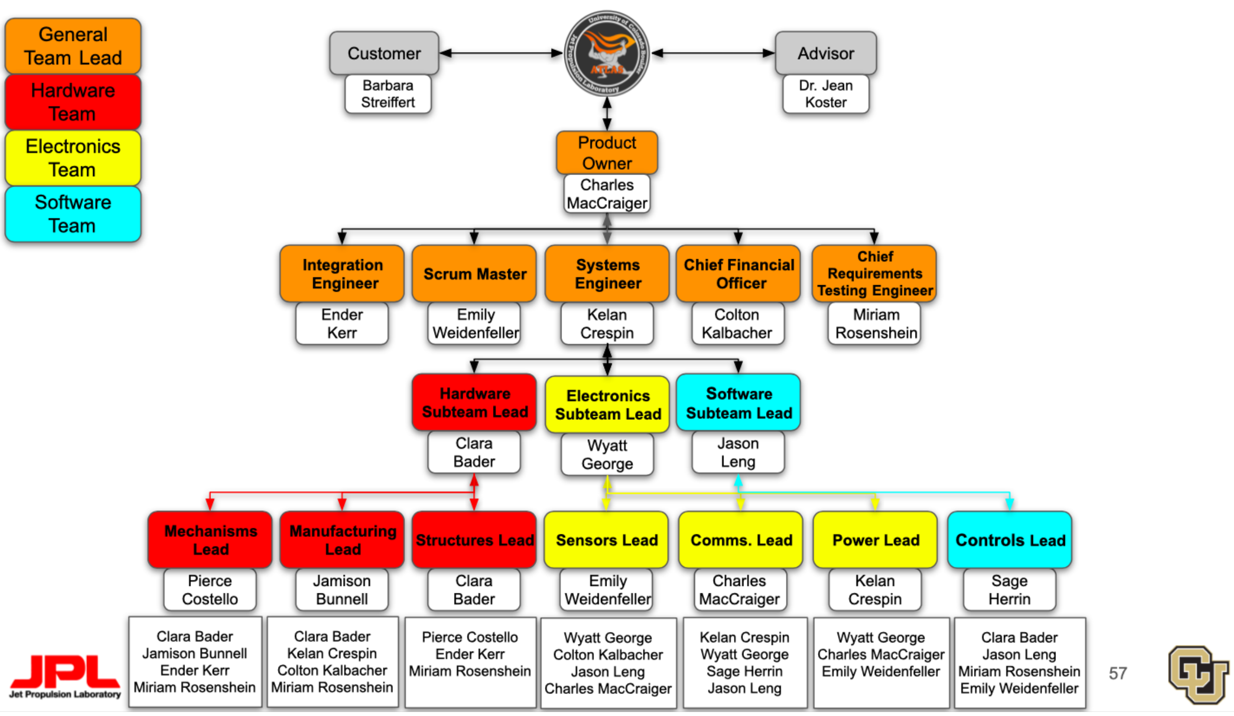


Figure 46: Organizational Structure

9.2. Work Breakdown Structure

The team's work breakdown structure is shown below. Highlighted in orange is the work the team has already completed. Highlighted in white is future work the team will be completing second semester. In red are the six main categories: Hardware, Controls and Software, Communications and Electronics, Integration and Tests, Fall semester Deliverables, and Spring Semester Deliverables. The categories were derived from the subteam break up and the schedule (first and second semester).

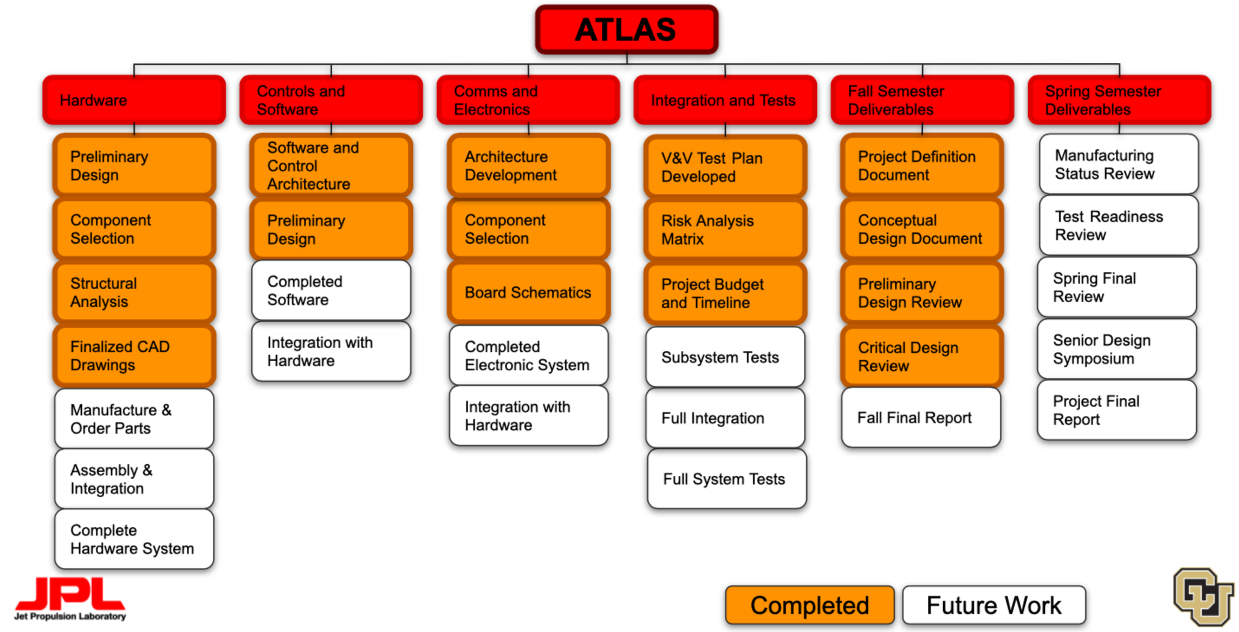


Figure 47: Work Breakdown Structure

9.3. Work Plan

Below the work plan is split up into two categories: Manufacturing and testing. The Gantt charts were created in the team's scheduling application, ClickUp. All tasks seen in the Gantt charts below are able to be assigned to team members, and seen in different views within the application. Assignments can be marked completed, as well as linked to other assignments though dependencies.

a. Manufacturing Schedule Figure 48 shows a high level view of the team's schedule. The sections highlighted in red represent the critical path, calculated by ClickUp. System integration is the main critical path, since all other sections are linked to it. Second semester started with the collection of all parts ("Management"). Then System integration began as the raw materials and necessary parts were acquired then appropriately manufactured. This original schedule encompassed the component testing (January), subsystem assembly (February - March), and testing (January to April). However, while many subsystem tests and validations did occur between the months of February and March, our progress and ability to continue project manufacturing as well as assembly were abruptly cut short due to global circumstances outside the projects team control. Therefore, the originally planned fully-integrated testing period was unable to take place as well, where the proper procedures regarding individual subsystem would have been followed.

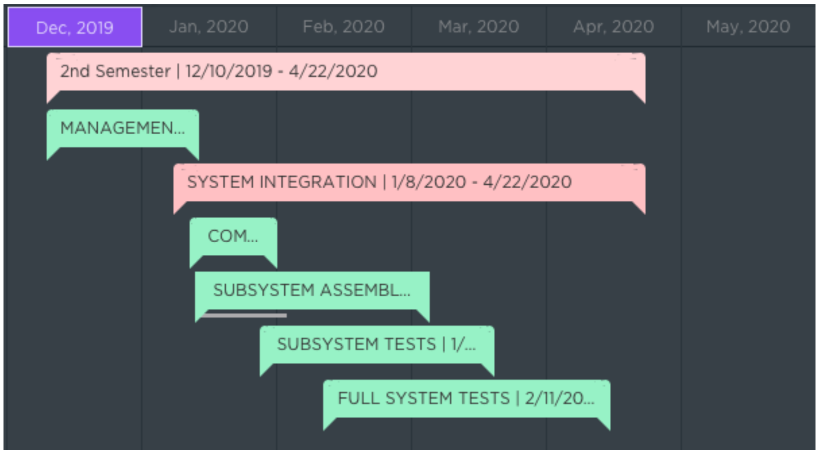


Figure 48: Gantt Chart: Overview

Figures 49 through 52 show the subsystem assembly plan. In purple are tasks related to software. In pink are tasks related to electronics. In yellow are tasks related to hardware. Light red represents team internal deadlines, while dark red restarted immediately on Jan. 13th, when the semester started. The deadline for subsystem assembly to be completed was estimated to be between Feb. 24th with an additional margin up until March 4th. The expectations of this original timeline would have been on schedule for the completion of the various subsystems based off current project progress estimations, given hardware and software testing were allowed to continue.

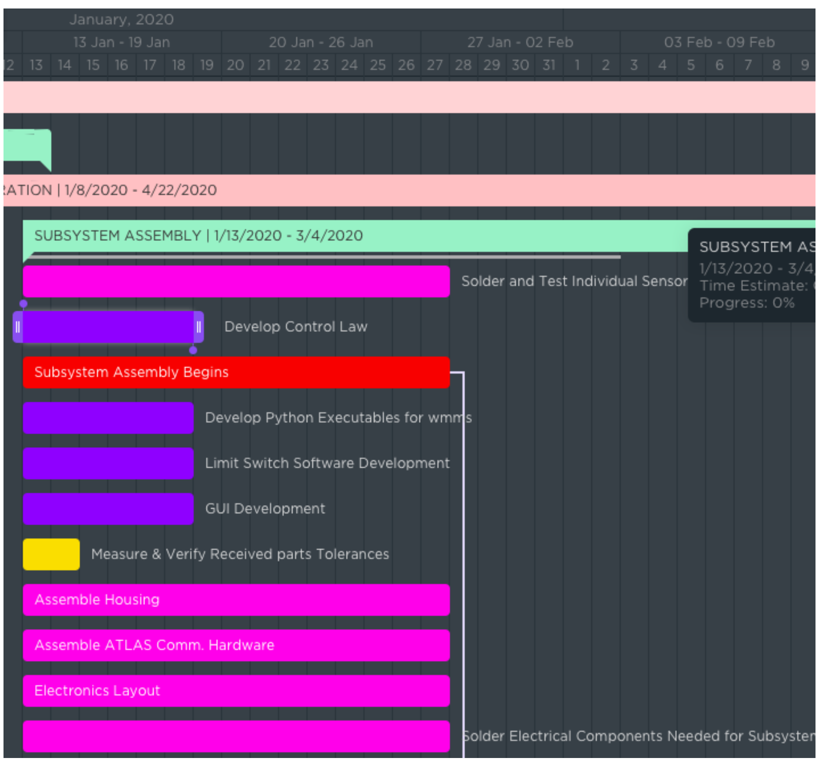


Figure 49: Gantt Chart: Subsystem Assembly 1

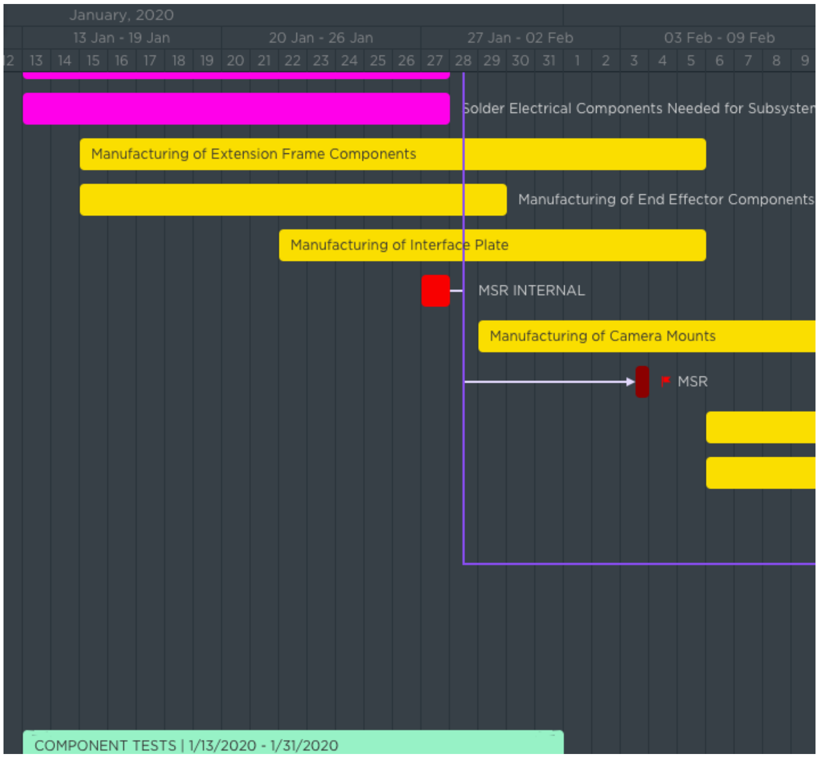


Figure 50: Gantt Chart: Subsystem Assembly 2

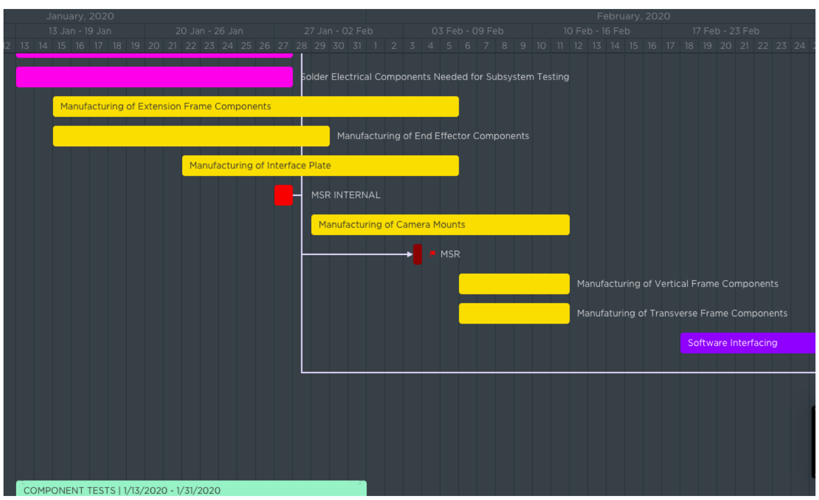


Figure 51: Gantt Chart: Subsystem Assembly 3

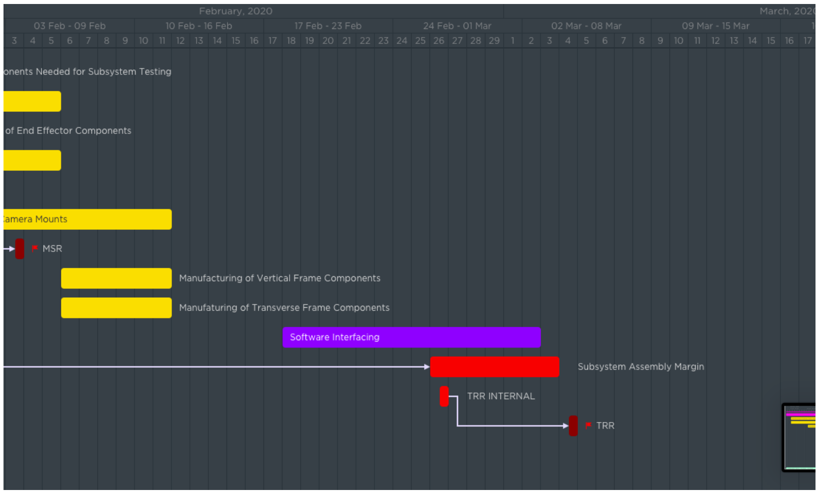


Figure 52: Gantt Chart: Subsystem Assembly 4

System integration was the most critical part of the schedule. Integration did start as early as March 3rd for hardware assembly, with various software that was ready to be integrated by the end of March. Due to the closure of the teams manufacturing capabilities, a full system integration between hardware and software was never fully realized.

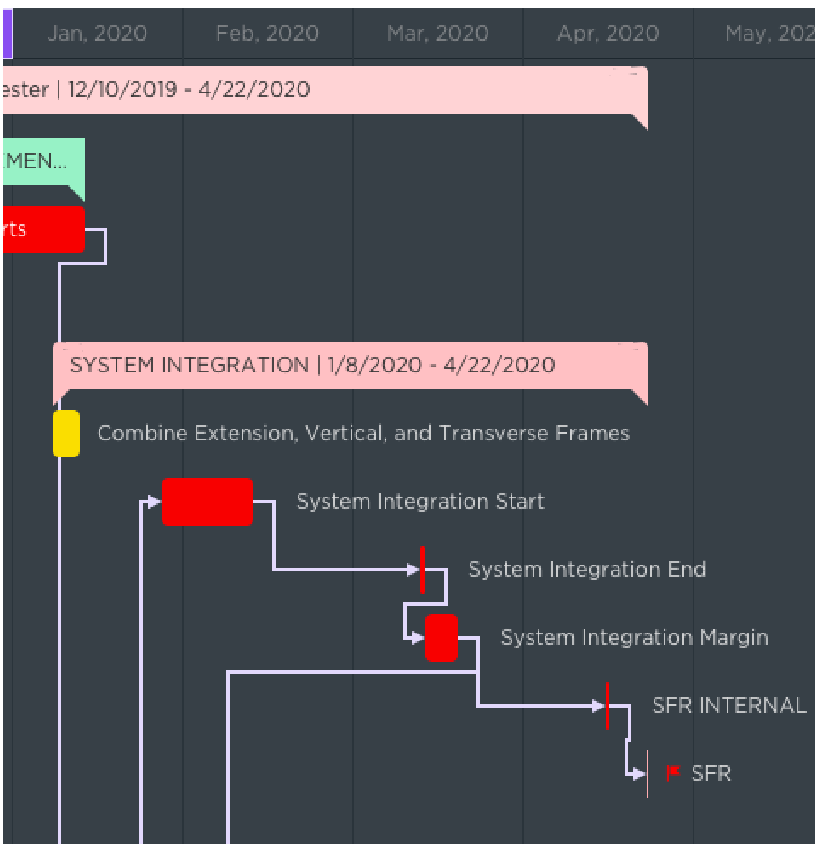


Figure 53: Gantt Chart: System Integration

b. Testing Schedule Below are the Gantt charts demonstrating component testing, subsystem testing, and full system testing.

Component Testing started at the beginning of second semester, as different materials and components were acquired. The final deadline was on January 28th with a margin up until March 1st. Each sub-team reported to be on schedule at the time, and was ready to move onto integration by March.

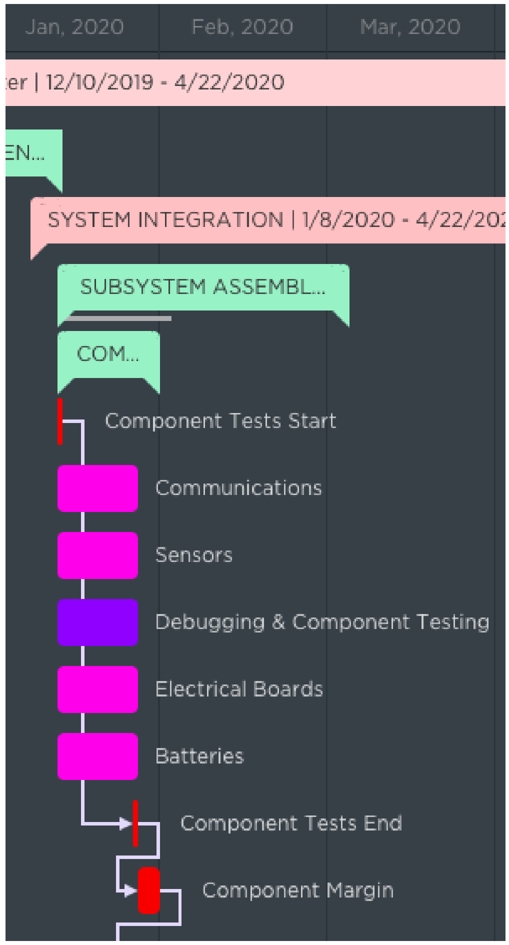


Figure 54: Gantt Chart: Component Tests

Subsystem tests started by January 20th and were largely completed by the deadline on March 12th, with a margin up until March 18th, before progress was ceased. These subsystem tests were also on schedule as originally planned for completion within the margin.

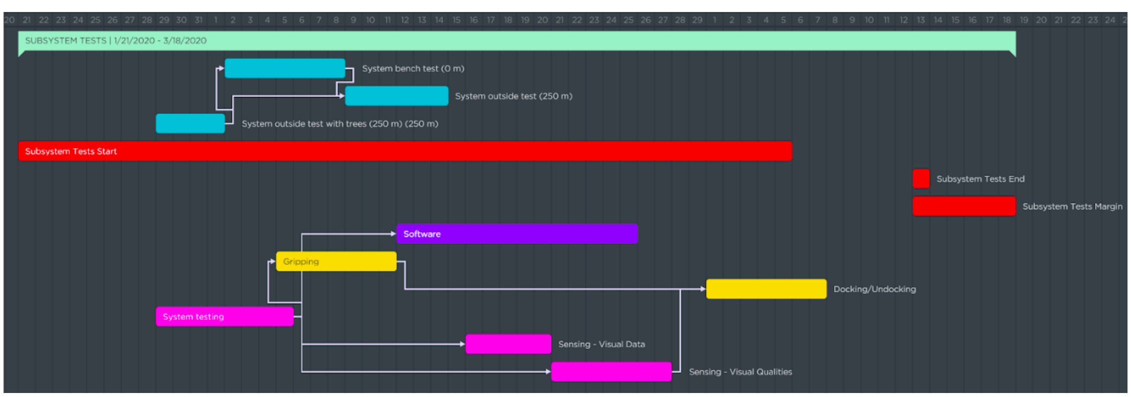


Figure 55: Gantt Chart: Subsystem Tests

Full System tests were planned to start on March 12th and had a deadline on April 9th, with a margin up until April 15th. Based off progress estimations, the team was covering good ground, and was likely to have met these deadlines within the appropriate margins. Soon after the to be presented at the Senior Design exposition.

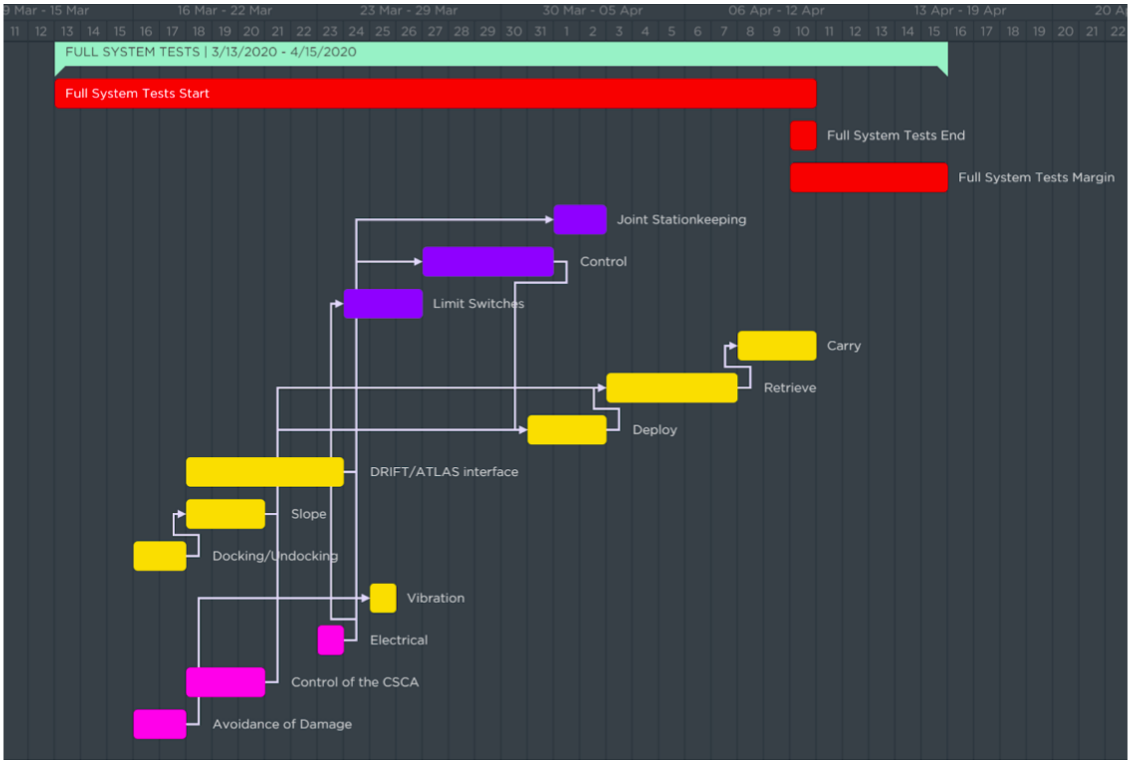
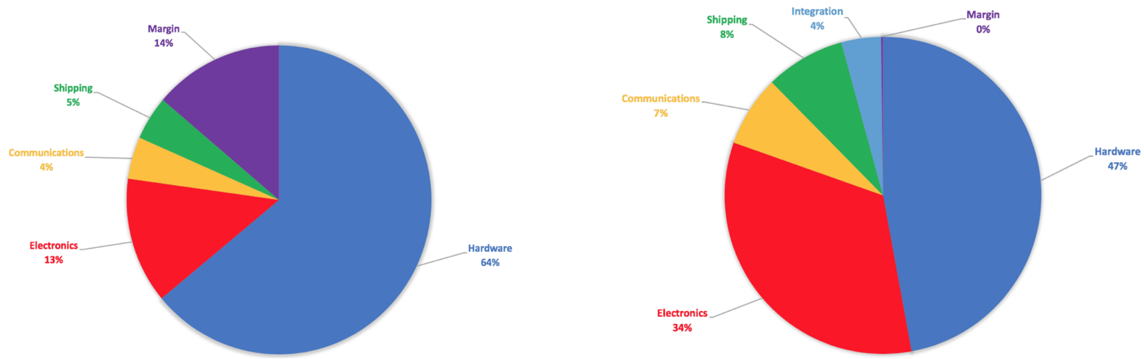


Figure 56: Gantt Chart: Full System Tests

9.4. Cost Plan

Author: Colton Kalbacher

The ATLAS project team was allotted an initial budget of $5000 from the University of Colorado at Boulder. Also additional funding of $1024 was acquired from the Fall 2019 Mini Proposal grant Engineering Excellence Fund (EEF), increasing the team total project budget to $6024. Based off the increased amount of budget available, and learning more about the project over time, the project scope of team ATLAS was revised slightly based off this new information to be better reflected in the new budget. Moderately better equipment, for both hardware and software, were able to be purchased, as well as accounting for a much high result for shipping costs than originally estimated. The final total financial spending for this project, as well as the original spending plan estimation, may be seen on Figure 57 which displays the total spending for each sub-team. Original sub-team estimations, shown on the right-hand side of Figure 57 were based off a compiled bill of materials gathered by each team after at the time. Actual sub-team spending may be seen on the left-hand side of Figure 57, and it may be seen that all additional spending that needed to be allocated to certain sub-teams was covered by the original margin of 20%.



Planned Budget:
(Before EEF Funding)

Hardware:	$3200
Electronics:	$660
Communications:	$220
Shipping:	$230
Margin:	$690
Total:	**$5,000**

Actual Budget:
(Including EEF Funding of $1,024 for total budget of $6,024 available.)

Hardware:	$2838.28
Electronics:	$2005.06
Communications:	$435.19
Shipping:	$489.72
Integration:	$243.72
Total:	**$6,011.97**

Figure 57: Planned vs Actual: All Sub-team Totals

10. Lessons Learned

Authors: Emily Weidenfeller, Jamison Bunnell, Miriam Rosenshein

10.1. General Team

The general challenges the team faced included tackling the schedule, building the leadership structure, writing requirements, and communicating across subteams.

With regard to the schedule, the team faced difficulties at the beginning of the Fall semester when different parts of the project were being designed. Some subteams ended up waiting on other subteams before starting and completing design work. This greatly pushed the schedule back. In order to mitigate this challenge, the team recommends having a preemptive backup plan for waiting subteams. Furthermore, increased interaction between subteams can help the whole team feel more involved and help spread general knowledge of the project. The second most challenging part was completing assignments ahead of time to increase the time allowed for revisions. It is recommended that internal deadlines be set far in advance, with discussion with all team members present. Internal deadlines can be a challenge to enforce, so there must be one-hundred percent agreement on the deadline and the positive purpose of having the internal deadlines.

Developing the leadership structure was a bit unclear, partly due to the large number of people on the project as well as the limited experience of the team members. It is recommended to future teams to establish all positions as early on as possible. Team ATLAS also prompted for co-leadership due to the large size of the team. Although the leadership was a bit unclear in the beginning it ended up working well.

Writing requirements was also a huge challenge but was found to be a great learning experience. The team learned that requirements should be kept as clear and concise as possible. The team also learned that it is important to define simple words, such as deploy, retrieve, and store, however, it is also possible to over define things. Having too many definitions can make requirements more difficult to understand.

Lastly, as stated previously, increasing interaction among subteams can be greatly beneficial to all members of the team. This increases understanding of all aspects of the project, and can help the team avoid potential problems when it comes to integration. The team experienced a some division among subteams that occurred naturally. This is something to keep an eye out for when working on future teams.

10.2. Hardware Team

One of the lessons learned by the hardware team throughout the two semesters was making sure parts were manufacturable. During the design phase in first semester the team did their best to make sure that it was possible to make parts, but it was sometimes difficult to anticipate the processes necessary for some of the more complex components. After gaining more knowledge about this throughout the two semesters, we would recommend that new seniors spend time researching the available methods of production. Future seniors may also consider meeting with Matt Rhode at the machine shop to review parts and get his professional feedback, as he was invaluable to the ATLAS hardware team. Understanding the processes that can be used to make parts would help a team in their design phase to make more reasonable parts.

It is also recommended that future senior projects teams with hardware-heavy projects be decisive in their design phase. At the beginning of the project we underestimated how long it would take to design the system, so we'd sometimes get backlogged in our decision-making. This caused some scheduling problems, but none serious enough to move the overall project behind schedule.

10.3. Requirements/Testing Team

The team learned that requirements are truly the driving force behind any project. Without clear, concise, NOT VAGUE, and testable requirements, a project is worthless. The requirements are a contract between a customer and the engineer. A good set of requirements defines the project exactly as it should be executed, and all design comes out of these requirements. Something future seniors should take the time to do is create a subsystem-to-subsystem interface requirements document. The team did not do this and it became increasingly difficult as the semester went on to keep track of what each subsystem needed from another.

Having clear, testable requirements also makes the second semester much easier. Every test must have success criteria and verify a requirement. If it does not have success criteria there is no way to say if it is successful or not. Additionally, if it does not relate to one requirement there is no point to that test.

11. Individual Report Contributions

11.1. Clara Bader

Levels of Success, Requirements, CDD-Forklift and Latching Mechanism, trade studies, overall editing, Vertical/-Transverse Frame writing.

11.2. Jamison Bunnell

Hardware Conceptual Design, End Effector Feasibility/General Writing, Manufacturing, Lessons Learned, Overall Editing

11.3. Kelan Crespin

Risk Assessment, Electronics - Preliminary and Conceptual Design, C&DH and Power Detailed Design

11.4. Pierce Costello

Trade studies, Extension Frame Detailed Design, Mother Rover Interface Detailed Design

11.5. Wyatt George

Electronics Conceptual Design, Electronics Detailed Design and schematic

11.6. Sage Herrin

Software conceptual design, Software detailed design, motor driver requirement satisfaction, stepper motor actuation calculations, software trade studies

11.7. Colton Kalbacher

Verification and Validation plans, Interface plate integration feasibility,Project Planning, Cost Plan, Overall Editing

11.8. Ender Kerr

Rotary Joint Detailed Design, CSR Interface Plate detailed design, MR integration detailed design, End Effector detailed design, Hardware Conceptual Design and trade studies, portion of Field of Application, Overall Editing/Formatting

11.9. Jason Leng

Software Conceptual Design, Software Trade Studies, Software Detailed Design, Software Manufacturing, Comms, C&DH Test Plans

11.10. Charles MacCraiger

Communications Conceptual Design, Communications Detailed Design, GUI Design, Formatting, and Editing

11.11. Miriam Rosenshein

Project Requirements and Levels of Success. CDD-Mechanical Gripper research, trade studies, Transverse frame feasibility, Verification and Validation test plans, lessons learned

11.12. Emily Weidenfeller

Project Purpose, Project Objectives and Requirements, Levels of Success, CONOPS, Order of Operations, Requirement Flow Down, CDD-Part of Programming & Video Camera, Design Process and Outcome - Video FOV, Position Feedback, Live Video Transmission & Display, Communication V&V, Project Planning, Lessons Learned

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Appendix