The University of Utah

Utah Robotic Mining Project

Systems Engineering Paper

Purpose Statement

Contribute to the advancement of space exploration and promotion of Science, Technology, Engineering, and Math (STEM) by designing and constructing an operable autonomous mining robot system for a simulation operation on Mars.

Team Members

Kaitlin Hall, Cole Mortensen, Zachary Oliphant, Rachel Phelps, David Purcell, John Robe, Justin Schramm, Max Stocking, Matthew Wilson, Fernando de Oliveira Lima Xavier, Samuel Zachary

Faculty Advisor: Jonathan Davies: I hereby certify that I have reviewed this paper prior to submission to NASA

Jonathan Davies

Introduction

Future advances in space exploration and development will require greater in situ resource mining and utilization. Launching materials from Earth's gravity well incurs a large majority of the cost for extraterrestrial missions [1]. If much of the materials could be mined and manufactured in situ, the costs decrease while the capabilities for growth increase tremendously, as in a Self-sufficient Replicating Space Industry (SRSI) [2, 3].

Recent missions to Mars have verified the existence of large deposits of water, primarily in the form of ice buried under the surface [4, 5]. With a reliable source of water and other consumables, extended robotic operations and human missions to Mars become safer and more inexpensive by not relying on resupply missions [6]. To mine and utilize these materials, advanced robotic capabilities will be required; for a Mars operation particularly, the large signal delays make near full autonomy critical. This challenge of mining on Mars has been constrained by the National Aeronautics and Space Administration (NASA) Kennedy Space Center (KSC) in the form of the Robotic Mining Competition (RMC). To solve this constrained challenge, we are applying principles of systems engineering and project management to develop a robust and reliable mining robot.

Contents

1 Pre-Phase A: Concept Studies

1.1 Lessons learned (2016 Phase F: Closeout)

After the 2016 competition, we conducted a post-mortem analyzing and documenting what went wrong and what we learned.

We identified two major improvements we can make: reduce the weight of our robot and make our autonomous mining sequence more robust. Our robot performed well, but it was entirely too heavy. We considered the weight of our robot to be an advantage; it would be more durable and could impart a larger digging force. During the competition, however, we were not able to offset the point cost from our weight by our increased throughput. Other teams, with lighter robots, were able to mine proportionally more.

Additionally, our autonomy system failed to perform during the competition. In rushing to get the mechanical build and electrical components integrated before the competition, we ran out of time to fully develop and test our autonomous system. We were able to develop some localization and navigation, but failed to bring together a full autonomous run.

Along with what we learned from our mistakes, we also picked up some interesting ideas from other teams, such as Akron's indicator LED lights and Iowa State's lighter tread system. Focusing on improving our system and incorporating other ideas, we began to design for the 2017 competition.

1.2 Design philosophy

Considering these lessons and our goals for this year, we are aiming for a lighter weight build and more robust autonomous system. We realized our 2016 robot was fairly well suited to be dropped out of an airplane—a bit overbuilt for the competition. Without sacrificing structural integrity and by choosing our materials more deftly, we are reducing the weight of our robot. Additionally, we are aiming for a more complete autonomous system that we can trust, with greater margins of error, to perform in the competition.

1.3 Trade-offs and analysis

With our design decisions and optimizations, we faced several trade-offs. To better understand and document the trade-offs faced in the design of the robot, we constructed a trade tree (shown in Figure 1) to assess higher level components. This graphic illustrates the advantages we identified of having a lighter weight build. By not accruing the point deduction for weight, we have a much greater margin in mining throughput and a better chance to score well in the chance of an autonomy failure.

Along with this broad strokes analysis, we have detailed a few of the major trade-offs that we faced during the design process. A more comprehensive list can be found in the Appendix

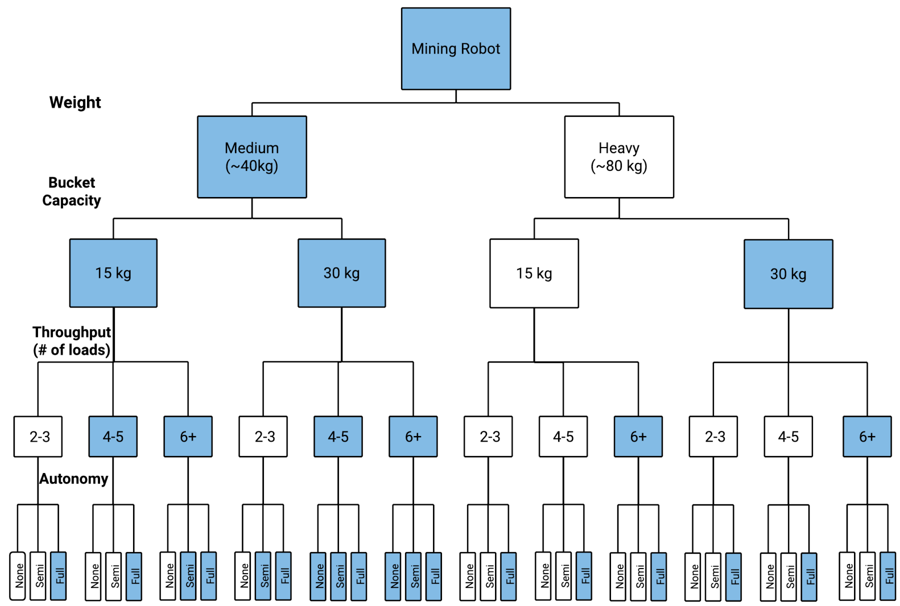


Figure 1: Trade Tree

1.3.1 Weight: Light vs Heavy

A heavier weight robot can impart a larger digging force, is less likely to tip with larger loads, and can be stronger and more durable. For a Lunar or Mars mission, however, heavier robots are more expensive to launch and the reduced gravities diminish the advantage of the heavy designs used on Earth [7]. These considerations, reflected in the competition's point deduction for weight, along with our experience last year, led to our decision to reduce the weight of our robot from 80 kg to approximately 40 kg.

1.3.2 Upgrade vs. New start

Upgrading last year's robot and making incremental changes and tests to the design would allow us to quickly test and verify new individual components and more easily carry out integration tests—especially beneficial for developing robust autonomy. A new start, on the other hand, would allow us to rethink the design and eliminate more subtle design flaws; we could better incorporate the lessons we learned from previous iterations. We discussed the upgrade approach and considered it in our concept studies, but we ultimately decided on the new start approach due to the difficulty of adapting all major components of our prior heavy system.

1.3.3 Teleop vs. Autonomy

For this competition, a human operator can likely mine more efficiently and reliably than any autonomous capabilities we will develop in the time frame. For real space robotics mining operations on the Moon or Mars, however, high levels of autonomy will be required. The teleoperation of a large number of mining robots, as might be used in a SRSI or related development would be unsustainable [2]; autonomy is the only viable option. With the competition's point value incentive and our team's interest in the technology, we decided to shoot for full autonomy, with the fallback to teleoperation available if needed.

1.3.4 Treads: 3D Printed vs. Commercial Off The Shelf (COTS)

Although we had some problems last year with the treads losing tension and slipping off, we decided to stick with the design for the greater traction and maneuverability the treads offer in the regolith. To both help the tensioning ability and reduce the weight from our 14.6 kg Honda snowblower treads, we came up with the idea to 3D print our treads. Designing and printing our own treads would require more research, design, and testing, but it would allow us more customization and modularity. They would be lighter, and we could easily prototype different shapes and materials and create custom links for precise tensioning.

1.3.5 Localization Strategies: Laser beacon system vs. Image processing vs. RF/time-of-flight

We also had to engineer a way for the robot to accurately localize itself in the competition arena for autonomous functionality. Previously this was attempted using QR codes and vision recognition on the collector bin, but that was unreliable due to the need to be facing the collector bin and the short range of QR code detection. To solve this, we researched the idea of using radio frequency or time-of-flight technologies such as a RFID beacon positioning system [8], but determined they would not achieve our required accuracy of 5 cm (Appendix: Table 7). The two technologies we primarily focused on are image processing using ArUco fiducial markers [9], and a custom beacon system, which uses a pair of panning lasers attached to the collector bin to localize the robot in the arena. The laser system was thought to provide more accurate positioning as it uses direct time of flight measurements, while the visual system relies on camera calibration and is subject to distortions. We decided to more heavily pursue the beacon system, but potentially use both technologies to gain higher accuracy and offer redundancy in case of system failure.

1.4 Work Schedule

We created a high level work schedule (Figure 2) with milestones and phases we hoped to complete by certain dates, leading up to the competition. This would allow us to make any necessary adjustments throughout the process to ensure we met all system requirements.

2 Phase A: Concept and Technology Development

2.1 System Hierarchy

We are following a similar design to last year's front end skid steer loader. To iterate on our dynamically adjusting center of mass system, where the upper assembly is actuated back and forth to allow easy digging and to prevent tipping when driving, we are switching from a linear actuator to a rack and pinion driven by a motor. For our electronics, we are using a 25V Lithium Polymer

ID	Task Name	Duration	Start	Finish
1	2016 Competition Analysis and Improvement Definition	73 days	Mon 5/30/16	Wed 9/7/16
2	Mechanical, Electrical, and Software Robot Feature Definition	16 days	Thu 9/8/16	Thu 9/29/16
3	**Mechanical Systems**	**106 days**	**Wed 9/28/16**	**Wed 2/22/17**
4	Basic Mechanical Design	11 days	Wed 9/28/16	Wed 10/12/16
5	Mechanical Systems in CAD	31 days	Thu 10/13/16	Thu 11/24/16
6	Review and Analysis of CAD Models	16 days	Fri 11/25/16	Fri 12/16/16
7	Prototype New Mechanical Systems	36 days	Wed 10/5/16	Wed 11/23/16
8	Adjust Mechanical Designs	11 days	Wed 11/23/16	Wed 12/7/16
9	Manufacture Mechanical System Components	26 days	Wed 1/18/17	Wed 2/22/17
10	**Electrical and Programming Systems**	**136 days**	**Wed 9/28/16**	**Wed 4/5/17**
11	Define and Select Electrical System Components	11 days	Wed 9/28/16	Wed 10/12/16
12	Prototype New Autonomous Systems	41 days	Thu 10/13/16	Thu 12/8/16
13	Define Software Components	11 days	Wed 9/28/16	Wed 10/12/16
14	Review and Refine Autonomous System Design	56 days	Wed 12/7/16	Wed 2/22/17
15	Install Electrical System in Mechanical System	11 days	Wed 2/22/17	Wed 3/8/17
16	Write Software Components	101 days	Wed 11/16/16	Wed 4/5/17
17	Test Mechanical and Electrical/Software System Integration	51 days	Wed 3/8/17	Wed 5/17/17
18	Trip To NASA KSC	3 days	Thu 5/18/17	Sun 5/21/17
19	NASA Robotic Mining Competition	5 days	Mon 5/22/17	Fri 5/26/17

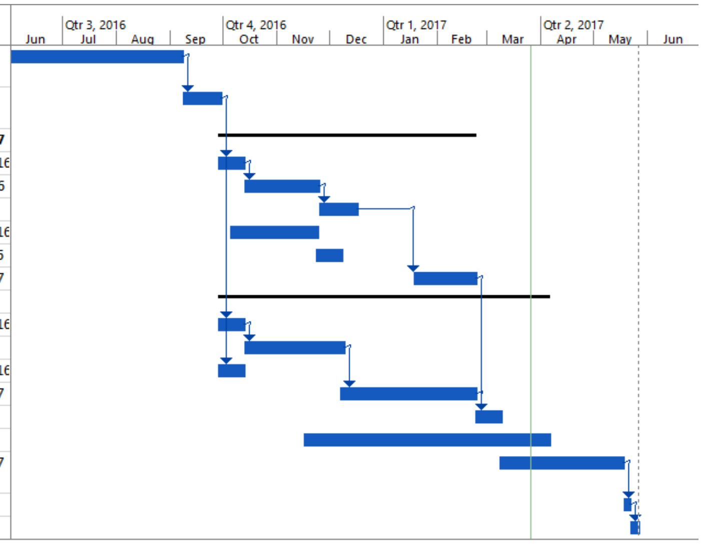


Figure 2: Gantt Chart of work from inception to competition

(Lithium Polymer (LiPo)) battery, NVIDIA Jetson TX1 computer [10], ZED stereo camera [11], and a custom beacon laser positioning system.

To document the complete breakdown structure of our system, we created a hierarchy diagram (Figure 3) that traces down all subsystems recursively, to discrete components (e.g., bucket, treads). The determination of this breakdown helped further define requirements and interfaces, discussed later in this document.

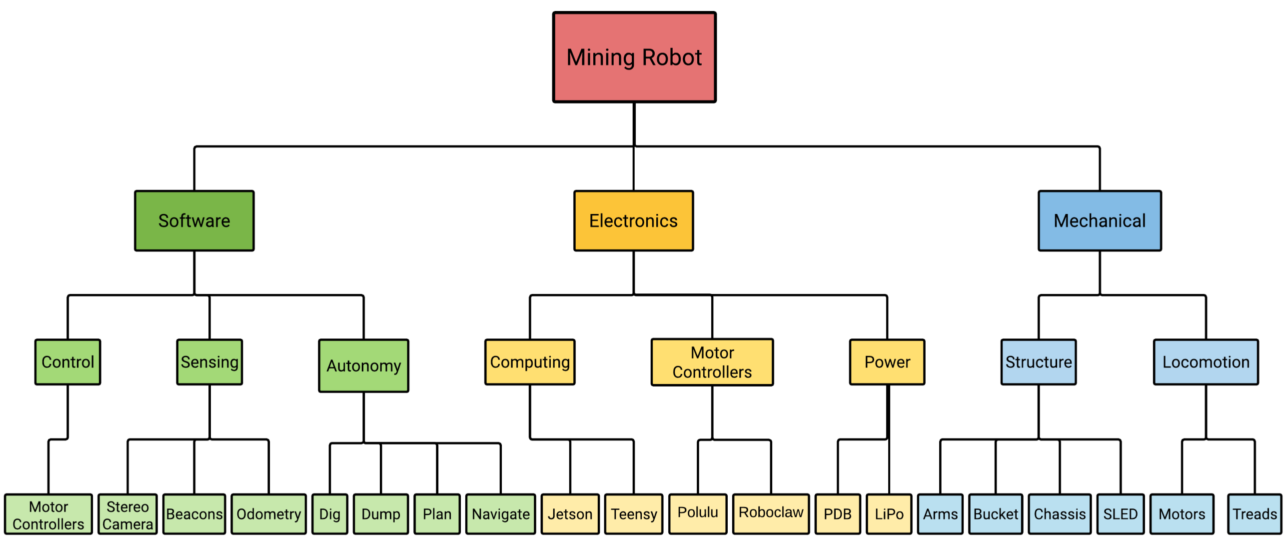


Figure 3: System hierarchy graph

2.2 Concept of operations

Our competition ConOps is broken down into three phases of operation: mission setup, mission operation, and mission takedown.

2.2.1 Mission setup

During the mission setup phase, the ground team will enter the arena, load the robot into the arena, and set up the network communication. As part of the setup, two ground team members will set up the beacon system on opposite sides of the collector bin by extending a known length of tether between them. This will guarantee we know the distance between the sensors, ensuring the accuracy of the positioning system. Another ground team member will start up the robot and maintain communications with mission control to ensure a successful connection. If any system does not boot properly or fails to gain communication, the procedure is to reboot that system.

While the ground team is setting up, the mission control team will enter the control room. The mission control team will connect to the router and initialize a GUI for robot control. If the robot has booted correctly and all status signals are good, they will radio to the ground team to exit the arena. If any problems are encountered, such as the robot or beacons failing to connect, the protocol is to communicate the failure to the ground team and request a reboot of the specified system.

2.2.2 Mission operation

Once the competition time has started, mission control will send a single signal to the robot to begin autonomous operation. The robot will carry out its operation while mission control monitors the status through the camera links and diagnostic messages from the robot. Through the GUI, the mission control team will be able to monitor the telemetry of the robot and using Robotic Operating System (ROS) tools, be able to visualize robot sensors data and monitor the 3D representation of the robot and its environment. If at any time, the robot is in danger of colliding with the arena or is failing to complete the mission, mission control will teleoperate the robot for the remainder of the mission.

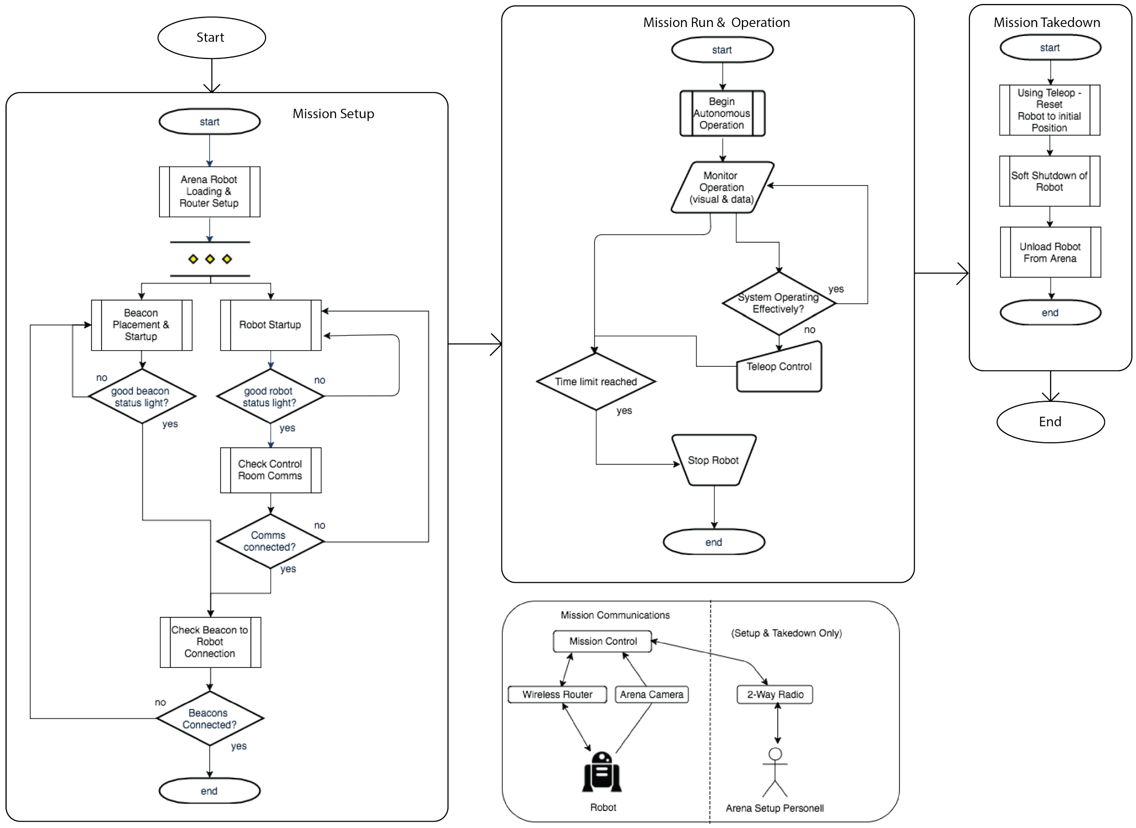
2.2.3 Mission takedown

After the competition round time has expired, mission control will send a signal to stop the robot. The robot will be returned to its starting location and recovered by the ground team. The team will shut down and secure the robot, recover all communications and beacon components, and finally clean the rover of all regolith before exiting the arena.

2.2.4 ConOps Flow Diagram

Figure 4 shows the detailed flow of all procedures during the operation of the system for each mission stage.

Figure 4: ConOps Flow Diagram



2.3 System Requirement Review (SRR)

2.3.1 Objective and success criteria

We conducted the System Requirements Review (SRR) to formalize our requirements and goals for the competition, fully document them, and establish an approach to track and verify that the system meets them. With this completed, we would be ready to continue on to the design process.

2.3.2 Process and Results

Upon entrance to the review, we had captured all baseline requirements to compete in the competition, defined in the Rules and Rubrics [5]. We had also informally established several further requirements and goals for the autonomy and mechanical design that our team wanted to achieve.

To help refine the requirements, we studied film from last year's competition [12] and revisited the relevant points of last year's post mortem for the ConOps, requirements, and goals for the competition. Stepping through all the processes and procedures for the competition run, we were able to further refine requirements, such as defining that the laser positioning system must accurately determine the orientation of the robot as well as the position.

Upon completion of the review, we had formalized our major requirements, identified several new subsystem requirements and devised verification approaches for our requirements. The results of the SRR, including requirement documentation, verification approaches, and related work are summarized in the following sections.

2.4 Requirements and Verification

2.4.1 Baseline and Higher Level Competition Requirements

Based on the rulebook and our major team goals, we developed our baseline requirements: those we need to meet in order to compete in the competition. Our shall statements, resolution status, and verification methods for the baseline and safety requirements are shown in Table 1. For a more comprehensive list of our requirements, such as for the autonomy subsystem, see the Appendix.

Table 1: Baseline competition and safety requirements

Requirment No.	Shall Statement (the system shall...)	TBD/TBR/Final + Method for resolution (if applicable)	Verification Success Criteria	Verification Method
B-1	Fit in a 1.5 m length x 0.75 m width x 0.75 m height.	Final	Robot, measured with a tape measure, is within limits	Measurement, Mechanical Model
B-2	Have a mass less than 80 kg; should be around 40 kg +/- 5 kg	To Be Resolved (TBR) After manufacturing and further design decisions are complete, the mechanical team will reevaluate to the final goal for mass	Robot mass, as weighed on a scale, does not exceed our limits	Measurement, Mechanical Model
B-3	Have a range of motion to lift the regolith up at least 0.6 m	Final	Robot succesfully dumps a bucket into the collector bin without damaging the bin	Mechanical Model, Demo
B-4	Deposit at least 10 kg of regolith in a 10 minute period	Final	Robot is deployed autonomously and observed to deposit 10 kg of regolith	Integration Test, Demo
B-5	Be deployable within 5 minutes	Final	Robot setup and connection is timed using a stopwatch	Integration Test, Demo

B-7	Display electrical energy usage with a Commercial off the Shelf (COTS) data logger	Final	Energy usage is observed before and after an operation to verify successful logging	Module Test
S-1	Have a red emergency stop system that cuts power to all motors	Final	Robot immediately stops all motion and kills power to the motors	Test, Demo
S-2	Include an easy way to disable rogue autonomy behavior	Final	Robot reliably exits autonomy mode back into teleoperation mode	Test, Demo
S-3	Have software limit controls on actuation	TBR By the autonomy team, when mechanical assembly is finalized	Limit controls don't allow movement beyond the specified range	Test

2.5 Interfaces

2.5.1 System interfaces

Our system and team organization is split among mechanical and electrical/programming subsystems. Major interface boundaries between the two subsystems include voltage level choice for motors and linear actuators, physical space in the structure for electronics, and mounting points for sensors. To handle these interfaces, the group leaders met to discuss the choices and come to a consensus. Figure 5 is an N2 diagram, which helps visualize these main interfaces, along with other inter-subsystem interfaces. Any design alterations in these components would have to be conscious of the potential impact on other subsystems.

2.5.2 Mechanical Subsystem

For the mechanical subsystem, the arm linear actuators must mate properly with the chassis and the arms; the chassis must mate properly with the wheels and treads; the bucket linear actuators must mate properly to the arm and bucket. To handle all such interfaces and ensure all component mates were worked out properly, we first modeled all components and assembled the robot in CAD software. We were then able to further refine things and make adjustments to the interfaces before manufacturing and building.

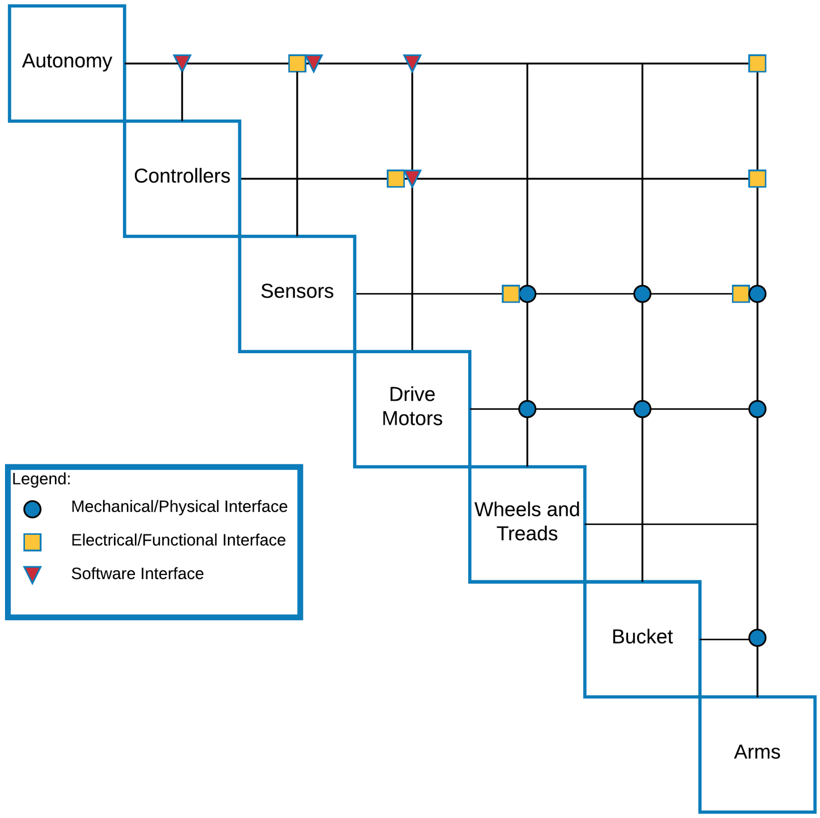


Figure 5: N2 Diagram showing bidirectional interfaces

2.5.3 Electrical Subsystem

The integration of the beacon sensors and the Inertial Measurement Unit (IMU) that Northrop Grumman generously donated to the team, was another large interface challenge. To relay the sensor data from the external beacons, we are establishing a WiFi connection to the robot's main computer using a wireless chip on the beacon microcontroller. For the Northrop IMU, we designed a custom Printed Circuit Board (PCB) to regulate power and relay data from the device. The data from this device then integrates into our software system to become a central component of our autonomous system.

2.5.4 Software Subsystem

To integrate the various software components of navigation logic, sensor integration and fusion, motion planning and control into a coherent system, we use ROS [13]. ROS allows us to develop and test components independently and integrate them using a standard communication protocol. Figure 6 shows a graphic, generated with ROS tools, that outlines how the software components communicate over communication channels called topics—such as the `autonomy` component subscribing to the `imu_data` topic, planning and making decisions on this and other data, then publishing a `cmd_vel` command to the `drive_motors` node to move the robot.

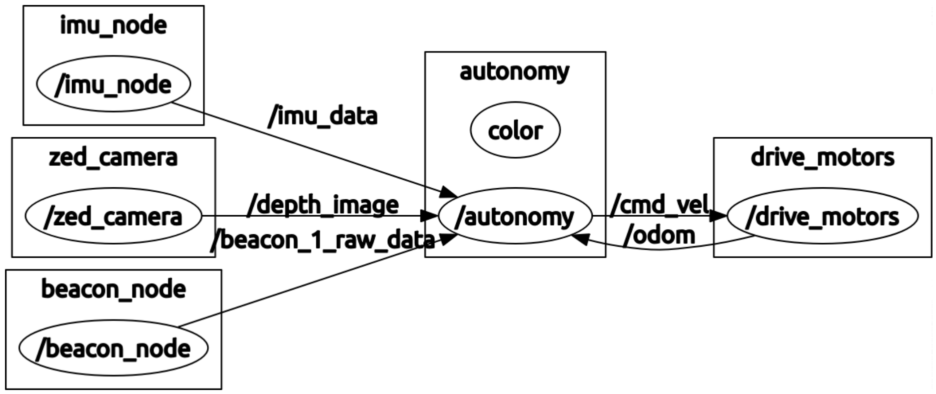


Figure 6: Simplified software interface structure generated with ROS's `rqt_graph` [14]

3 Phase B: Preliminary Design and Completion

3.1 Preliminary Design Review (PDR)

3.1.1 Objective and success criteria

We conducted the Preliminary Design Review (PDR) review to get a proof of concept on all new technologies and ensure that designs were on track to meet requirements in the scheduled time.

3.1.2 Process and results

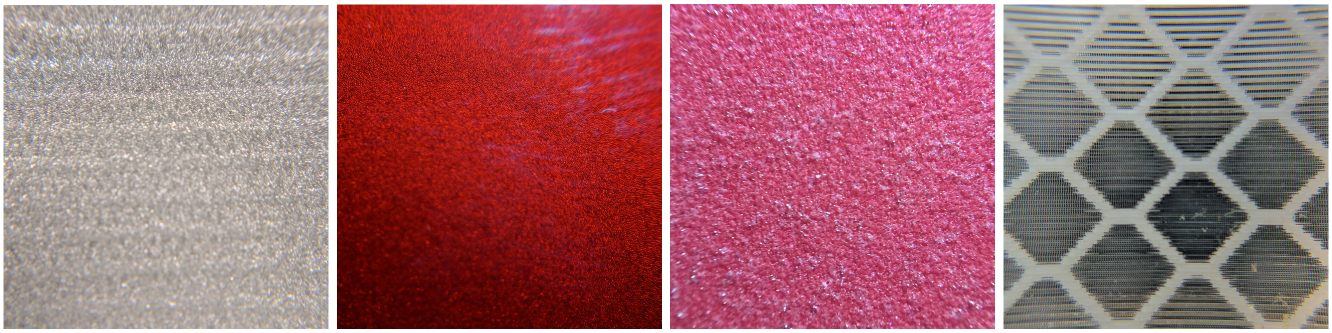
The two major new technologies we were developing for the competition, the beacon and the 3D printed treads, needed extensive preliminary tests to verify they warranted further development and were going to meet requirements.

3.1.2.1 Beacon Tests

The beacon system uses a pair of Garmin Lidar Lite V3 distance measurement sensors [15] attached to corners of the collector bin that pan across the arena to recognize a high reflectivity value on the robot's surface. Upon recognizing this value, the beacons relay the corresponding distance and angle measurements to the robot so the robot's position can be determined.

Upon entrance to this review, we had selected several retro-reflective materials that we could attach to the robot. During the review, we conducted several tests to determine which materials' reflectivity values had a high enough contrast with the surrounding environment.

In our tests, we found that the beacons did not measure consistent reflectivity and distance values from many of the materials we chose. The fabric treated with reflective ink reported erroneous distance values of 1 cm while providing strong reflectivity values; the red retro-reflective tape measured values in the 200 cm range when the real values were below the 80 cm range; and the reflective spray paint material was reflective in the visible light spectrum but was indiscernible from its surroundings to infrared laser light. From these results, we found that a material that is reflective to human perception does not necessarily translate to the material being reflective to infrared light.



(a) Material treated with 3M Reflective Ink - Series 8000 [16]

(b) 3M Scotchlite tape

(c) Reflective spray

(d) 3M IR Reflective tape

Figure 7: Materials used for testing the beacon system

The test data revealed that the distance measurements from the beacon contain noise. To make this data usable on a robust autonomy system more research methods to process and filter the data are needed. With these extra considerations, we continued on the development of the beacon system, along with onboarding an alternative such as HTC Vive Lighthouses [17] or primary use of a visual localization system using ArUco fiducial markers [9].

3.1.2.2 Tread tests

Upon entrance to the review, we had worked out the design of the treads. Each tread consists of 30 3D printed tread links that are joined by nylon pins and wrapped around the wheels. We printed two full sets of treads using Polylactic Acid (PLA) (a somewhat brittle plastic that prints more quickly), and several links using Thermoplastic Polyurethane (TPU) (a more flexible material) [18].

Our new chassis and drive system were not available, so we tested the PLA treads on our old robot base. We immediately realized the failure of the brittle PLA when we tried to drive the robot up a small cement obstruction and several links on both treads shattered. After replacing the broken links and continuing the test, we found that the printed tread design worked well; the treads could turn sharply without binding up, did not slip off, and offered sufficient traction in the sand. We found that they did sink into the sand when digging, so to help counteract this, we increased the width of the links in future prints to increase surface area.

We concluded that we would switch to exclusively TPU which would deform from stresses and impacts, rather than shatter. To test the limits of the TPU in comparison to the other materials, we conducted pullout tests in an Instron tensile tester at the University of Utah. Figure 9 clearly illustrates the superiority of the TPU links in tensile strength compared to the other materials.

Figure 8: Tread sand tests [19]

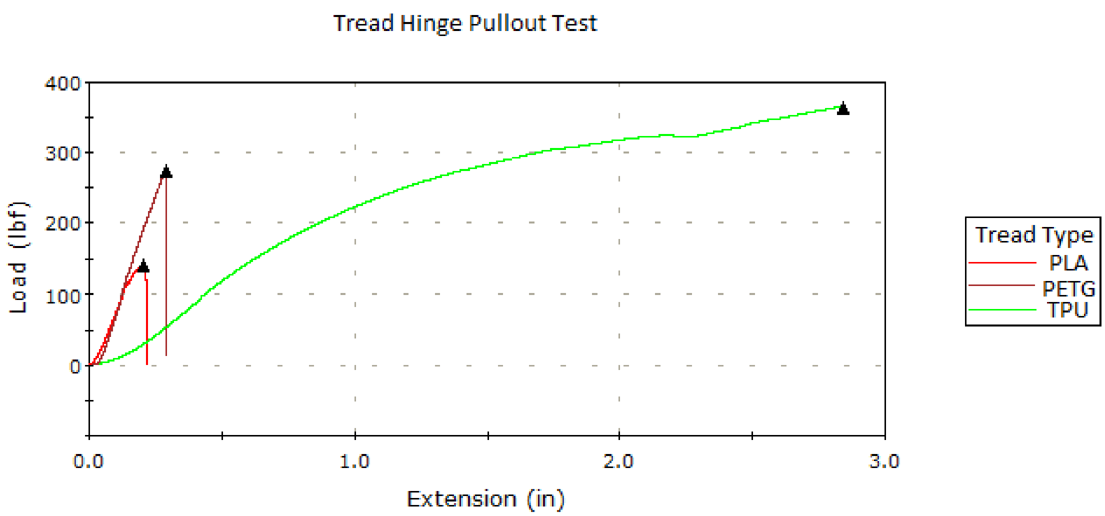


Figure 9: Tread Hinge Pullout Test

4 Phase C: Final Design and Fabrication

4.1 Critical Design Review (CDR)

4.1.1 Objective and success criteria

We conducted the Critical Design Review (CDR) to assess whether all design and fabrication were on track for completion. We planned to finalize all verification testing and procedures and take extensive inventory of tasks and timelines to meet requirements for the system. It was crunch time.

4.1.2 Process and results

4.1.2.1 Manufacturing

Upon entrance to the review, we manufactured the key mechanical components such as chassis, arms, bucket, rack and pinion, and treads. Although we were behind our ideal work schedule, we assessed that we were still on track to complete the robot with enough time to sufficiently test the integrated electrical and software systems and to develop a robust autonomous system.

4.1.2.2 Verification planning

With the knowledge we had gained from testing and the adjustments that were made with the system, we iterated on and finalized the verification approaches to ensure a successful mission. We revisited our requirements documentation and went over what verifications still needed to be resolved and on what timeline they should be completed. Many components relied on prerequisite components being complete, so we also redirected attention to expedite these processes. The results of this review are summarized in the following section.

4.2 Verification of Requirements

For the baseline requirements for weight and size, our CAD modeling shows we are within range, but as we begin assembling the robot in the next few weeks, we will measure these and verify that the robot meets these requirements.

To verify the range of motion and baseline movement requirements (Table 1), we will integrate the electrical system we have been developing to establish a teleoperation control system. With this, we can test that the robot has the desired range of motion and can move reliability in sand.

To verify that our autonomy will meet all requirements and be robust enough to handle the randomized starting positions and stochastic conditions of the competition, we will be conducting extensive testing in an outdoor practice arena we constructed this past summer. We built this test area to competition arena specs so we could practice and run tests in near competition conditions. Here we can get feedback on the development of our autonomy components, so we can quickly iterate and improve.

After the independent modules of digging, dumping, and navigation have been developed to a sufficient level, we will do full integration tests, simulating a competition run. We will start the robot in various conditions with obstacles in the arena, and run the autonomous operation to monitor its behavior.

Another technology we have developed to facilitate verification and testing for autonomy is a Gazebo simulation of our robot (video here: [20]), including simulated motion controllers and sensors such as an IMU and depth camera. Simulating our robot allows us to quickly iterate on algorithms and autonomous operations without having to transport the robot to the testing arena and set up all networking components. There are some disadvantages of using simulation, namely its inability to fully model the complete environment, and its lack of models for fine particles, such as dirt. It does, however, offer quick prototyping and safer testing, without the risk of damaging our robot before the competition.

5 Phase D: System Assembly, Integration, and Test Launch

5.1 Reliability and Risk Analysis

To succeed in the competition, our robot needs to operate for the two 10 minute competition rounds, many testing scenarios, and operation at outreach events. The base mechanical components and electrical systems, including treads, digging components, power system, and teleoperation software, must be reliable for our robot to do well in the competition. If they are not, then autonomy and further goals are irrelevant. To ensure the reliability of the base components, we are conducting numerous tests, as outlined in Sections 2.4, 4.2. We are also analyzing the potential risks of failure of each component.

We created a risk matrix that shows the estimated probabilities and consequences of subsystem failures at the time of writing this paper. The matrix is meant to illustrate what is currently on track for reliable execution (green), what must be given attention (yellow), and what must be focused on to avoid system failure (red). Autonomy, though not required to succeed in the competition, is given larger weighting to represent our team's goals.

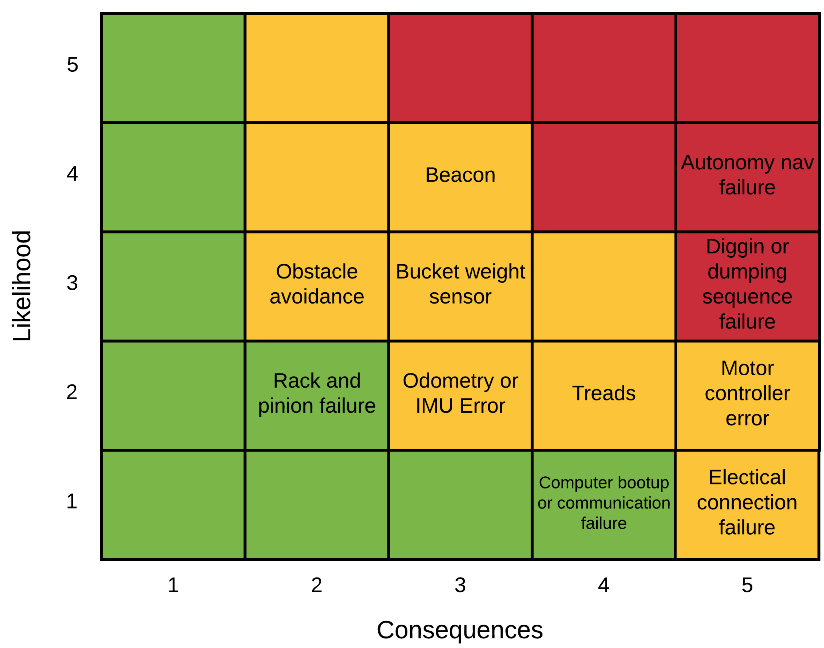


Figure 10: Risk Matrix

We see that the rack and pinion failure and computer boot up both entail acceptable risk and are on track to be reliable for the competition. Components such as the beacon, tread, and obstacle avoidance failure are given higher risk values, as these systems are newer and require more refining and testing. Electrical connection and motor controller failure are given high consequence rating, but seem unlikely points of failure. The autonomy features are given equally high consequence, but have much higher likelihoods of failure because they are more complex components.

5.2 Technical Budget Analysis

5.2.1 Mass

For our allocated mass budget, we state our 40 kg goal. For estimated mass, we added the recorded masses of each component and calculated a total of 38.4 kg. The figure in this case might be an underestimate, for some minor components may not be recorded.

5.2.2 Power

5.2.2.1 Allocated

The system must have enough power to run for 10 minutes. Our battery has a capacity of 5800 mAh and max discharge rating of 145 A. With a capacity of 5800 mAh, the max current we can draw continuously during the 10 minutes of competition is given by: $5.8Ah = I(10/60)hrs$. This yields: $I = 5.8Ah * 6hrs^{-1} = 34.8A$. Thus, we can use 34.8 A for 10 minutes of the competition before our battery dies. For a 25V power source, this equates to $34.8A * 25V = 870W$ of power.

5.2.2.2 Estimated

We used the spec sheets of our motors to calculate an over estimate of power usage. The max currents we expect to draw from each component are listed in Table 2

Table 2: Electronic Current Draw

Component	Current draw (A)	Quantity	Total Current (A)
Linear Actuators	2.5	4	**10**
Drive Motors	2.2	4	**8.8**
Rack and pinion motors	0.5	2	**1**
Computing and sensors	1	N/A	**1**

Using these values, we then incorporated the expected percentage use of the components during the competition to estimate total power use (we are only driving the linear actuators for perhaps 20% of the competition time). We came up with rough estimates of 20% time use for the linear actuators, 80% for the drive motors and 10% for the rack and pinion motors and 100% for the computing and sensing. This equates to $10A * 0.2 + 8.8A * 0.8 + 1A * 0.2 + 1A * 1.0 = 10.24A$. At 25V, this becomes $10.24A * 25V = 256W$ of power.

5.2.3 Data

5.2.3.1 Allocated

We do not want to use more data than the point equivalent of 15 kg of regolith for the added benefit of monitoring autonomy and for the backup teleoperation mode. Data usage incurs a one point penalty for every 200kb/s used. 15 kg of regolith amounts to 45 points, so the conversion is $45 * 200 = 2250 kb/s$ [5]. Thus, we want to use no more than 2250 kb/s of bandwidth.

5.2.3.2 Estimated

For the estimated data use, we recorded the bandwidth of all data we would monitor during the competition using our Gazebo robot simulation model, which communicates many of the same data topics as our final robot will. We also added the additional 400 kb/s for the situational awareness cameras [5]. The measurements are shown in Table 3.

Table 3: Simulated data bandwidths

Software message components	Data bandwidth (kb/s)
Camera image (compressed)	450
Depth cloud (from stereo camera)	175
Joint states	14
Odometry	25
`tf` (robot pose data)	40
Miscellaneous/Unaccounted for	200
Total	904 + 400 (for competition cameras) = **1304**

5.2.4 Summary

Table 4: Technical budget summary

	Allocated	Estimated
Mass	40 kg	38.4 kg
Power	835.2 W	256 W
Data	1304 kb/s	894 kb/s

6 Phase E: Operations and Sustainment

During the practice runs and competition, in order to diagnose and analyze any errors that occur, we will be collecting as much data as we can. To analyze how the robot is performing mechanically, we will set up a camera to record footage. To diagnose any autonomy or internal robot software errors, we will record all relevant communication on data topics sent over ROS, using the `rosbag` tool. Collecting data with "rosbags" allows us to later replay and analyze all data that the robot receives and generates during the competition; we could replay all data from the competition round in simulation and interactively alter parameters to see how they affect the system. These data collection methods will greatly facilitate any debugging and corrective adjustments to the system that may be required.

7 Cost Budget

Our total expected cost expenditure was $11,500. Table 5 shows the breakdown expected expenditures for each category of the system compared with the actual expenditure based on purchase orders documentation. The travel expenses include the cost of a van for the trip to Florida, which has not been purchased yet.

Table 5: Cost budget summary

	Expected ($)	Actual ($)
Mechanical	4000	2679.94
Electrical	4000	2749.79
Travel	3500	1419 + Van ($\sim$ 1900)
Total	11500	8748.73

References

[1] NASA. The tyranny of the rocket equation. [Online]. Available: https://www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.html

[2] P. Metzger, "Space development and space science together, an historic opportunity," *Space Policy 37.2, 77-91 (2016)*, 2016. [Online]. Available: https://arxiv.org/abs/1609.00737

[3] P. Metzger, A. Muscatello, R. P. Mueller, and J. Mantovani, "Affordable, rapid bootstrapping of the space industry and solar system civilization," *Journal of Aerospace Engineering 26.2, 18-29 (2013)*, 2016. [Online]. Available: https://arxiv.org/abs/1612.03238

[4] NASA JPL, "Mars ice deposit holds as much water as lake superior," Nov 2016. [Online]. Available: https://www.jpl.nasa.gov/news/news.php?release=2016-299

[5] NASA. NASA's Eight Annual Robotic Mining Competition Rules and Rubrics. NASA Kennedy Space Center.

[6] NASA - in-situ resource utilization. [Online]. Available: https://www.nasa.gov/exploration/analogs/isru/

[7] S. Siceloff. NASA - engineers building hard-working mining robot. [Online]. Available: https://www.nasa.gov/topics/technology/features/RASSOR.html

[8] C. C. K. Travis Deyle, Matthew S. Reynolds, "Finding and navigating to household objects with uhf rfid tags by optimizing rf signal strength," 2011. [Online]. Available: http://pwp.gatech.edu/hrl/wp-content/uploads/sites/231/2016/05/iros2014_in_home_rfid_deyle_reynolds_kemp.pdf

[9] S. Garrido-Jurado, R. M. noz Salinas, F. Madrid-Cuevas, and M. Marín-Jiménez, "Automatic generation and detection of highly reliable fiducial markers under occlusion," *Pattern Recognition*, vol. 47, no. 6, pp. 2280 – 2292, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0031320314000235

[10] Embedded systems developer kits & modules | NVIDIA jetson | NVIDIA. [Online]. Available: http://www.nvidia.com/object/embedded-systems-dev-kits-modules.html

[11] ZED stereo camera. [Online]. Available: https://www.stereolabs.com/

[12] M. Wilson, "Robotic mining project NASA RMC competition footage 2016." [Online]. Available: https://www.youtube.com/watch?v=tsUz3quMwMI&list=PLiimmqwRyeDDlTa1e5yEe9xI4RfTz-J-s&index=1&t=149s

[13] M. Quigley, K. Conley, B. P. Gerkey, J. Faust, T. Foote, J. Leibs, R. Wheeler, and A. Y. Ng, "Ros: an open-source robot operating system," in *ICRA Workshop on Open Source Software*, 2009.

[14] D. Thomas. rqt_graph package summary. [Online]. Available: http://wiki.ros.org/rqt_graph

[15] LIDAR-lite v3 - SEN-14032 - SparkFun electronics. [Online]. Available: https://www.sparkfun.com/products/14032

[16] 3M. 3m reflective ink - series 8000. [Online]. Available: http://multimedia.3m.com/mws/media/60920O/reflective-ink-tds-75-0500-2635-2.pdf

[17] V. M. Vilches. 0.3mm indoor localization with ros and htc vive. [Online]. Available: http://www.ros.org/news/2016/08/03mm-indoor-localization-with-ros-and-htc-vive.html

[18] Thermoplastic polyurethane. [Online]. Available: https://polyurethane.americanchemistry.com/Introduction-to-Polyurethanes/Applications/Thermoplastic-Polyurethane/

[19] M. Wilson, C. Mortensen, and M. Stocking. 3d printed tread sand testing. [Online]. Available: https://goo.gl/photos/XVXpRHYVxeWfLPyD9

[20] M. Wilson. Utah robotic mining project gazebo simulation demo. [Online]. Available: https://youtu.be/CdpFUFFlBOw

Acronyms

CAD	Computer Aided Design
CDR	Critical Design Review
COTS	Commercial Off The Shelf
IMU	Inertial Measurement Unit
KSC	Kennedy Space Center
LiPo	Lithium Polymer
NASA	National Aeronautics and Space Administration
NiMH	Nickel Metal Hydride
PCB	Printed Circuit Board
PDR	Preliminary Design Review
PLA	Polylactic Acid
RMC	Robotic Mining Competition
ROS	Robotic Operating System
SRR	System Requirements Review
SRSI	Self-sufficient Replicating Space Industry
TBR	To Be Resolved
TPU	Thermoplastic Polyurethane

A Trade-off Table

Table 6: Trade-off table

Choice	Selected	Considered	Reason
Onboard computer	NVIDIA TX1	Intel NUC	Integration with stereo camera
Battery	LiPo	NiMH, LiFPo	Weight
Sensor	Stereo camera	Onboard lidar	Better in environment without walls
Wifi antenna	Commercial	Custom designed	Ease and use case
Motor controllers	Roboclaw	Phidgets	Reliability
Bucket actuation	Linear actuator	Motor and gear	Ease of implementation
SLED	Rack and pinion	Linear actuator	Range of motion and speed

B Comprehensive list of requirements

Table 7: Autonomy requirements

Requirement No.	Shall Statement (the system shall...)	TBD/TBR/Final + Method for resolution (if applicable)	Verification Success Criteria	Verification Method
A-1	Localize itself within 2-3 in (5 cm) of it's true location with respect to the collector bin	TBR After more qualitative testing of system by autonomy team	Data recorded by the system is measured against the true position using a tape measure.	ModuleTest
A-2	Navigate from the collector bin to dig and back after digging, accurately ending within a few inches at the collector bin to dump.	TBR After initial testing and prototyping	Robot can autonomously drive back and forth several times between the bin and dig area in our practice area without getting lost.	Module Test
A-3	Avoid all obstacles in the arena by driving around them	Final	Robot drives around varying size of obstacles	Module Test
A-4	Dig a sufficient amount of regolith in each scoop and have a way to measure how much is in the bucket	TBR After initial feasibility testing	Robot, in test arena, can consistently and safely dig a sufficient amount of regolith	Module Test
A-5	Dump full payload into bin without damaging the bin	Final	Robot consistently dumps all dirt in bin and doesn't contact bin edge	Module Test
A-6	Integrate all subcomponents in a coherent run (i.e. planning)	Final	All systems operate together and the system completes a full run	Integration Test
A-7	Not use walls	Final	Run the robot in an open area and test performance	Integration Test

A-8	Handle partial system failure with system redundancy	TBR After more development and module testing	Handles failure of one sensor module, such as beacon	Informal

Table 8: Dust and miscellaneous requirements

Requirement No.	Shall Statement (the system shall...)	TBD/TBR/Final + Method for resolution (if applicable)	Verification Success Criteria	Verification Method
D-1	Not kick up dust when driving	Final	Robot drives through the arena without kicking up much dust	Inspection
D-2	Not be vulnerable to dust	Final	Robot does not pile dust upon itself and is sealed to prevent components from being damaged.	Analysis, Inspection
D-3	Not kick up dust when digging	Final	Robot digs regolith without stirring up much dust	Inspection
M-1	Not use physical systems that will fail on Mars	Final	System does use GPS, rubber pneumatic tires, air/foam filled tires, open or closed cell foam, or ultrasonic proximity sensors	Module Test
M-2	Not use any processes that alters the physical or chemical properties of the BP1 or gravel.	Final	No trace of robot operation is left, besides displacement of dirt.	Integration Test
M-3	Not use the wall to push the dirt up against to collect	Final	Robot is capable of digging without walls	Integration Test
M-4	Supply all of its own power	Final	Robot is powered by onboard battery system	Demo
M-5	Should attempt to dig deeper for more icy regolith	TBR When we have done some initial testing and considered if this will yield higher output	Robot autonomy or teleoperation have ability to dig past the upper regolith to reach the icy regolith.	Integration Test, Inspection