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Team Members

Ashton Archer
Lydia Barrett
Briton Bauerly
Troy Blackwood
Charlotte Brandenburg
Erik Branyon
Sandy Bremer
Christian Brown
Julius Chirchir
Chaz Clark
Bonnie Cunningham
Arthur Dahlquist
Jonathan Duffy
Alek Erickson

Louis Faivre
Kiera Fodor
Tyler Friesen
Daniel Galinovskyi
David Gonzalez-Gimenez
Zachary Gordon
April Graves
Jakob Hayt
Nicholas Hasto
Dalton Headlee
Tanner Holte
Nemeer Jaleel Padiyath
Lucas Jedlicka
Sebastian Kazun

Brandon Keesling
Paul Larsen
Daniel Lee
Michael Leedy
Cameron Lynch
David Mahler
Taylor Meyer
Eric Middleton
Colin Mikulec
Lucio Mireles
William Nickoloff
Alex Nielsen
Andrew Okumah
Kevin Oran

Matthew Pedretti
Luke Peterson
Matthew Rapnikas
Ricardo Rodriguez-Menas
Anthony Ruperto
Christian Schierbrock
Isaac Stahr
Timothy Steward
Jacob Stewart
Joseph Talley
Ryan Thompson
Taylor Tuel
Eric Weirup
Charles Wickham

The faculty advisor has read and reviewed this document prior to submission.

Jim Heise

CSM Faculty Advisor: Jim Heise
Abstract

With the goal of encouraging the development of innovative robotic excavation concepts for utilization of resources found on Mars, NASA has established the annual Robotic Mining Competition. The Iowa State University Cyclone Space Mining team has taken up the challenged posed by the competition since its inception eight years ago. The current team, consisting of 57 members with 8 different majors, has spent the 2016-2017 competition season designing, manufacturing, and testing their newest installment of robotic mining system called HERMES 4. The new system was influenced by the goals of addressing the problems of the previous mining robot design and creating a high production, high efficiency model. A description of the systems engineering process for the robotic mining system and supporting information is provided. Renderings of the dual robot system in different operational configurations are presented below.
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Introduction

As humankind considers the possibility of extraterrestrial habitation, Mars has been identified as an ideal target planet for the implementation and testing of necessary technologies and strategies. Access to water is one of many requirements for survival in the Martian environment. Water can be extracted from granular minerals and ice located in the regolith already on Mars. The resource recovery process is known as In-Situ Resource Utilization (ISRU). Further applications of ISRU include shelter construction, life support, and fuel for return or outward trips. One popular strategy for obtaining the valuable minerals and soil is through the implementation of mining robots.

Competition Problem Statement

To promote the development of regolith mining, NASA has established the annual Robotic Mining Competition (RMC). Starting on May 22, 2017, the eighth annual NASA RMC will be held to demonstrate the newest advancements and innovations of participating teams. To compete, the robotic mining system must be able to excavate and store the regolith simulant (BP-1) and/or the ice simulant (gravel). The material must then be deposited into a collection bin. The entire process mimics the challenges of navigating the Martian terrain due to the abrasive characteristics of the regolith simulant and inclusion of surface obstacles. NASA specifies operating requirements for vehicle mass, vehicle size, minimum material collection amounts, dust tolerance, communication, and autonomy. The exact RMC requirements and further mission goals developed by CSM are summarized in Table 1.

Our Experience

The Iowa State University team, Cyclone Space Mining (CSM), will be returning for its eighth consecutive competition year. Having competed every year since the outset of the NASA RMC, the team has learned from its many successes and failures. Initially, reliable operation in the regolith simulant posed a great challenge until designs for the drive system, excavation system, and operational center of gravity were improved through multiple years of experience and research. In recent years, CSM has focused on providing innovation through new operational strategies and efficiencies. Notably, CSM has been working towards operating its system with a “swarm” mentality by fielding multiple robots. The team also continues to work towards implementation of a fully autonomous mining system. While these improvements have merit, past robots have often not met their full potential due to mechanical and network failures. A failure analysis of the 2016 RMC has led CSM to focus on developing all systems of the robot to fully accomplish the mission requirements and provide a professional demonstration of system capabilities as desired by NASA.

System Philosophy: Descent with Modification

The mission of a robotic mining rover is fundamentally different from that of existing exploratory NASA rovers. The overarching goal is to move large quantities of material, not to gently explore an extraterrestrial world. Due to the nature of the mission, a much more industrial vehicle is required. CSM treats their design as such, choosing to build a robust and capable rover that is intended to handle extreme conditions and a variety of essential tasks. The team has endorsed an industrial type design through a strategy of continuous improvement. For example, once the method of excavation and locomotion used were found to be competitive, focus was shifted towards system improvements rather than
additional research into other possible methods. Continuous improvement has allowed the team to iteratively solve issues with the design and push it towards its full potential rather than starting from scratch on new concepts each year. A brief analysis of the generations of Cyclone Space Mining robots shows a progression of large modifications to smaller ones as the design matured.

Descent with modification has also been inspired by CSM’s desire to present a robotic mining rover capable of thriving in a larger production system required for the expansion to Mars. For practical colonization of a nearby object like the Moon, approximately 10 metric tons of oxygen are required to support two lunar landings per year. The requirement is calculated considering life support for four person crews, fuel cell consumables, and return trip propellant [1]. Since an expedition to Mars is much farther, the fuel estimate would be even larger.

When conceding a commonly cited 1% regolith to oxygen conversion factor [1], a good case for supplying a high production, high efficiency system can be made. CSM has always focused on accelerated collection rates and continues to work towards this goal through advancements in strategy, digging efficiency, collection capacity, and more.

For the 2017 NASA RMC, Cyclone Space Mining has worked towards further improving last year’s robotic mining rover, the High Efficiency Regolith Mining and Excavation System (HERMES) 3 [2]. The team has also identified several issues within the organization as a whole, developed strategies, and implemented solutions to produce the new and improved 2017 competition model, HERMES 4.
Deliverables

The deliverables that CSM has identified for the 2017 competition season are outlined in Table 2.

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Delivery Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systems Engineering Paper and Outreach Project Report</td>
<td>4/10/2017</td>
</tr>
<tr>
<td>Slide Presentation and Demonstration</td>
<td>4/18/2017</td>
</tr>
<tr>
<td>Video of mining robots in operation. Video will include at least one full collection cycle</td>
<td>5/1/2017</td>
</tr>
<tr>
<td>Documentation describing basic mining robot information, operational details, safety hazards, and a basic parts list.</td>
<td>5/1/2017</td>
</tr>
<tr>
<td>Regolith collection system adhering to 2017 RMC constraints</td>
<td>5/22/2017</td>
</tr>
<tr>
<td>Robot control system capable of autonomous control of the mining robots with optional manual control capabilities</td>
<td>5/22/2017</td>
</tr>
</tbody>
</table>

Table 2: Chronological summary of project deliverables

System Architecture Overview

The Cyclone Space Mining robot system can be broken down into two fields: Mechanical Systems and Control Systems. Each of these top-level function groups can be broken down into several additional levels of subsystem assemblies. The system hierarchy is outlined below in Fig. 1.

Concept of Operations

The HERMES 4 Concept of Operations are developed in accordance to the NASA RMC rules and the strategy of CSM. First, HERMES 4 will be placed in the starting area with the orientation stated by the judges. Each robot will then be powered on and a connection will be established over the network. At competition start, the autonomy program will be executed and each robot will traverse the obstacle area, excavate material in the mining area, and return to the collection bin and unload the regolith while confirming the location of the other robot to prevent collision. This process will be repeated for the duration of the 10-minute competition run. Should the autonomy fail at any point during the competition, manual control will be used to ensure a successful round. Upon completion of the run, information regarding the energy and power usage will be recorded by team members and reported to judges. At that time, both robots will be removed from the testing arena and inspected to determine what, if any, servicing is required.

Systems Engineering

Figure 1: Diagram of system hierarchy of the regolith mining rover
Phase A: System Studies and Concept Development

Each of the two robots fielded by CSM for the 2016 RMC suffered identical catastrophic failures during mining operations. The failure mode was first encountered during a test run prior to the competition. During the dumping portion of the mining cycle, a frame member began to visibly bend at a welded joint. Operations were stopped and the robots were analyzed. The failure was believed to have occurred due to a mechanical interference between two components in the lift system. The frames were patched and the problem was believed to be fixed. However, during the competition runs both robots were incapacitated when a similar failure occurred elsewhere in the lift system.

Although the failures were mechanical in nature, they were caused by an interaction of many factors. A root cause analysis revealed several areas to focus on improving for the next generation of HERMES robots. The DFMEA, located in Appendix A, indicated five major potential failure modes: frame member fractures, motor damage, track fracture/slippage, software failure, and autonomy failure. Using the failure analysis, CSM compiled five overarching design goals that, together, address the potential failure modes. Fig. 2 depicts these design goals, which include reliability and durability, accessibility, maintainability, testing, and system management.

Reliability and Durability

Building a truly robust system requires further analysis of the loading experienced by various systems on the robot during mining cycles. The system must be able to withstand worst-case scenario loading under any competition circumstance. Furthermore, the system must be able to operate for extended periods of time and withstand not only static stresses, but also dynamic stresses and cyclic fatigue. The lack of deep knowledge about the system limits contributed to the failures experienced in the 2016 RMC. Further structural analysis of the robot components must be performed to address durability.

Dust intolerance was another factor that impacted the reliability of the HERMES 3 robots. Many parts, including the track tensioners and drive motors, have an increased risk of failure if compromised by regolith intrusion. This intolerance necessitated

Figure 2: Ishikawa Diagram for main causes of failure at the 2016 RMC
secondary sealing methods, typically by applying electrical tape, to prevent the intrusion of dust to the system. In addition to possible part failure caused by dust penetration, the frames and bogies accumulated large quantities of regolith. Constant contact with the regolith degraded the components at an accelerated rate, allowing excessive wear and tear to the system. For the new design, it was determined that more durable and permanent sealing methods must be developed for key components of the robot such as the electronics, motors, tensioners, and actuators. Components that are in close contact with regolith, such as the bogies and frames, should be sealed or have channels in them allowing the regolith to exit, creating an easy-to-clean system.

**Accessibility**

While generating design goals, the control team conducted a survey of CSM’s active membership to assess team needs and requests. The survey found that amongst the membership of 55 students, only five members felt confident they could operate the robots. Without the ability for multiple members to operate the robots, testing and training became almost impossible. Updates to the control system must enable general members to use the robots for testing and research. To improve accessibility, the design must improve operating interfaces.

From the network perspective, the 2016 design made two decisions that hampered accessibility. First, the decision to use TCP, an accurate and slower communications protocol, limited the ability to do server discovery. Second, the decision to make the robot behave as a client required hard-coding the server addresses in the embedded code. These decisions meant the robot would only talk to one predetermined computer unless someone logged in and changed the settings file. Few general members had the skill set to do this, and testing and operation became a full-time job for the software developers who wrote the network code.

Another obstacle for the team was the power system. The 2016 design made the transition from brushed motors to brushless motors. The change also upgraded the power system to 42 V and high-capacity lithium polymer batteries. The new motor controllers use large capacitor banks to provide for the brushless motors. These factors led to an inrush current that killed the solid-state relay days before competition. The solution implemented last year was not ideal; a switch and resistor were placed in parallel in line with the main power rail. On startup, the switch was open, forcing all the current across the resistor and preventing the high-current scenario from before. Then the switch was closed, bypassing the resistor. Thermistors were also placed in line with the main power rail to prevent the inrush current. This solution impeded accessibility by requiring members to know an additional startup procedure.

**Maintainability**

A key design flaw within HERMES 3 was the maintainability of the system. Previous CSM rovers have been difficult to service after final assembly. Although they were designed to behave as a modular system, practical experience showed that disassembly for maintenance was very time consuming. To eliminate this problem, the new design must include subsystems that can be completely detached with ease. This will enable easy replacement of parts, allowing CSM to test new concept parts or to quickly replace components in the case of failure.

Another flaw found within the HERMES 3 system was the high variety of fasteners. The inconsistency of fastener types led to increased costs since more fastener variety requires more spare parts. Efficiency was decreased while working with the robot since a member would need to pause to identify the correct fastener or tool. Electrical connectors used in the control system were also varied and tedious to work with. To improve maintainability, the new system needed to standardize connectors and fasteners.
Testing

Testing is a vital part for the development of effective designs. Design and fabrication must be completed in time to verify that the systems meet their respective requirements. Each subsystem needs to be examined individually so that problems can be isolated and identified before the assembled system is tested.

The lack of regulated testing procedures has historically been problematic, with most of the testing being performed hastily and with poor documentation. Proper testing requires forethought and experiment design. For example, it is difficult to isolate and test the forces created by digging up regolith without a dedicated measurement setup that involves specialized tools and measurement devices. Without regulated procedures, competing concepts cannot be properly compared. Updates to the testing plans of CSM must allow for the quantitative comparison of subsystems of different designs or generations.

System Management

Poor time management has inhibited Cyclone Space Mining in some way every competition year. Several common management issues that affect most student projects needed to be addressed in order to prevent them from continuing to negatively impact the final design. Too much time had been previously spent in the beginning of the year for the design process, leading to rushed manufacturing and eliminating opportunities for critical system testing and evaluation. Instead of maintaining its own schedule, CSM relied too heavily on NASA regulated deadlines. An administrative-level solution was required to improve the health of CSM’s system management, and in return, many other aspects of the program.

Design Review 1:

The preliminary design review was used to set up the goals and expectations for the design of HERMES 4. During the review, the team compared past Cyclone Space Mining scores to the scores of other schools. The team also reviewed the 2017 design goals, the proposed system hierarchy, and the concept of operations for the mining competition. What testing would be conducted and how it would influence the design was also covered. The feedback focused on top-level systems and how they could be improved to better meet mission requirements. Team leadership was pleased with the recommended goals and advised the group to transition to Phase B.

Phase B: Design Processes

Management Process

The design process employed by CSM went through several upgrades. To enable testing time, the team analyzed the expected and actual project timelines from previous years to identify opportunities to reduce waste. For example, time was often lost due to lead times on ordered parts. Waiting periods were reduced by scheduling important design decision deadlines and component orders before school breaks. This reduced the time spent in the design phase by roughly six weeks over the 2016-2017 season. To drive accountability, more frequent design reviews were held and fallback review dates were established to reduce the risk of missing NASA RMC deadlines. While several setbacks were encountered due to outsourced manufacturing delays, test facility reconstruction, and university mandated facility move, a significant improvement in the quality of work has already been seen. The Gantt chart located in Appendix C specifies each phase of the project as it was completed. The team also created a regulated test planning document that streamlined preparations for tests and improved documentation. A sample test planning form can be seen in Appendix A.
Mechanical Process

Drive Base

Frame

To address the durability issues experienced by the HERMES 3 frame, several material options were explored. 4140 chromoly steel was considered as a replacement material for the frames, which have been constructed with 6061 aluminum tubing in previous years. The steel frame concept would have increased the reliability of the frame, but would have also increased the weight significantly. Several machined frame components would need to be converted to steel for the frame to be welded. The weight added by these machined components made the steel frame concept undesirable.

It was decided that 6061-T6 aluminum would be used for frame members to optimize the frame weight and strength. The team was able to create a frame concept that matched the strength of the steel frame while outperforming it in weight. For this concept, the tubing size and cross sectional area were increased. This concept also required that the frames be heat treated after welding to remove the heat affected zone at welded joints and to ensure that the frames had a T6 strength throughout.

The HERMES 3 suspension was found to have stability issues; after careful review it was decided a suitable trade-off to improve stability and reliability of HERMES 4 would be to eliminate the current suspension design and revert back to a fixed track system similar to that of HERMES 2. This design simplification allowed resources to be directed towards improving the track drive system, another area of less-than-perfect reliability on HERMES 3.

Drive Module

The team also sought to make improvements on the drive system. For HERMES 3, a system consisting of two planetary stages, an intermediate bevel gear stage, and a chain drive was used. This system was effective, but was large, heavy, and required additional sealing methods.

Several new design concepts were explored with the goal of shrinking the physical space claim, reducing the weight, and improving the sealing mechanisms. Two main concepts were considered: a strain wave gear system, commonly known as a Harmonic Drive, and a planetary system. The strain wave gearbox imposed several limitations. The gearboxes being considered had to be run in a wet housing and had extremely tight manufacturing tolerances. Furthermore, the strain wave gearboxes could not reliably withstand the high speed generated by the SL-MTI motors that had been used previously with great success.

The second concept consisted of three planetary stages contained inside of the drive cog. By relocating the planetary stages, this concept could mimic the physical size of the strain wave concept while eliminating several of the risks introduced by the nature of strain wave gears. Size comparison of the 2016 and 2017 drive modules is shown in Fig. 3. The planetary concept would also allow for the use of existing SL-MTI drive motors, which offer exceptional power and speed for their size. For these reasons, it was decided to pursue an internally contained planetary gearbox.

Figure 3: A comparison of the 2016 drive system (upper) with the new 2017 drive system (lower). Both systems are shown at the same scale.
Regolith Handling

Hopper
The material used to make the hopper was also reconsidered during the design of the 2017 robots. Over the last several years riveted aluminum hoppers were used. However, the possibility of switching the hopper panels to carbon fiber was considered this year. The carbon fiber concept would be lighter than aluminum, which would allow for reallocation of weight to more critical areas.

Multiple factors were considered while evaluating the carbon fiber and aluminum hopper concepts. The flow rate across the hopper was tested for both aluminum and carbon fiber. The results of this test suggested that with the appropriate surface finish, a carbon fiber hopper would be able to mimic the regolith flow rates of the aluminum hoppers from past years. Methods of increasing the flow rate were also investigated. These methods included adding or increasing draft on all faces of the hopper, applying a low-friction coating to the interior of the hopper, and applying vibration to the hopper and collected regolith.

A large factor impacting the hopper material decision was previous experience and concerns with manufacturability. CSM did not have sufficient experience working with carbon fiber and the test data did not support a large enough advantage to make this material shift viable for the 2017 season. For these reasons, the decision was made to move forward with an aluminum hopper with geometry optimizations and an internal low friction coating. The vibration method was deemed too high risk because of the potential of loosening mechanical and electrical connections.

Conveyor
The PVC belted conveyor used by CSM in past competitions has proven to be very reliable. However, the PVC belt is relatively heavy and is not considered a space ready material. The PVC belted conveyor also uses injection molded drive teeth, and new molds would be necessary for its continued use. Alternate conveyor designs were considered to help reduce weight, to drive part commonality, and to take another step towards achieving a more space-ready design.

A new Dual Component Metal Bucket (DCMB) concept, seen in Fig. 4, was generated. The DCMB draws heavily from the Single Component Metal Grousers (SCMG) used in the track system. Because the tracks have performed reliably in testing, this concept was extended to the conveyor system. The new concept replaced the injection molded drive teeth with stamped steel drive teeth that were made from the same die set as the track grousers. The DCMB concept would also allow further flexibility with the belting material.

Figure 4: A scoop section from proposed digging conveyor

Both concepts would use the same bucket and drive tooth combination. Because of the reduced weight and the opportunity to reduce non-space ready material, the team intends to use a layered steel shim stock belt with the DCMB concept. However, testing will be completed to confirm the reliability of the new belt before it is deemed competition ready. In case of a steel belt failure, the conveyor system is designed to be able to accept a PVC belt as backup.
**Actuation**

The linkage system that joins the regolith handling system with the drive base underwent a major redesign. Because this subsystem serves as the interface between two major mechanical systems, it needs to be extremely robust. A math model was developed to allow the team to better understand the scale of the forces acting on the system during all stages of the mining cycle. The interface of the linkage simulation is shown in Fig. 5. During this study, it was discovered that the magnitude of the forces exerted on the robot during the digging phase were much larger than previously estimated. To safely accommodate these loads, a new linkage design was required. For HERMES 4, the team sought to improve the four-bar linkage actuator system by removing the bending stress loads and welded members.

Apart from simply redesigning the individual components, the geometry of the entire linkage was improved to allow for faster dumping and improved stability during mining. Multiple concepts were considered, including replacing welded tube members with machined or sheet metal parts. These concepts were evaluated based on their strength and weight, and on the speed, cost, and complexity required to manufacture. Although using machined parts would have allowed for a further reduction in weight, it would have also increased the manufacturing time and cost significantly. Team members had experience working with sheet metal components and were able to create a concept that met the strength requirements and was able to be produced quickly, with a high degree of accuracy, at a low cost. The sheet metal linkage system was selected for the final design.

**Electrical Integration**

Previous designs did not give enough consideration to control hardware; control enclosures and mounting space were typically added only when the mechanical design was complete. To meet its maintainability goals, the team chose locations and designed enclosures for the electrical components so they were appropriately protected during operation. By including the electrical hardware in the mechanical design from the beginning, the electrical and control systems were better integrated with the mechanical systems.

The inclusion of electrical hardware in the design allowed the team to identify potential changes to the frame and hopper to provide adequate space for the electrical components. Past iterations of HERMES robots have typically included a combination of 3D printed ABS control enclosures and metal mounting panels. The decision was made to replace all 3D printed ABS enclosures with sheet metal enclosures due to the added strength and durability. The strength of the enclosures was critical in allowing for the exploration of new mounting locations, such as inside the track envelope. These locations were traditionally considered high risk because of the dynamic nature of the tracks. With more durable electrical enclosures, CSM made use of this otherwise lost space.

**Control Process**

**Hardware**

**Power Management**

Power management had not been seriously addressed in previous years. Generally, CSM handled power with only a few simple components. While the inrush problem was fixed for the competition, it showed the need for a well-designed power system. To that end, a secondary controller was designed, responsible only...
for managing the robot energy. The team called the secondary controller the Smart Management of Robot Energy (SMORE).

**Central Carrier Board**

The carrier board was completely redesigned for the new processor and wiring system. The new design needed to designate I/O for specific purposes, whereas the 2016 design had generic peripheral connectors. By creating a carrier board with specific ports for the different systems on the competition bots, the control team improved the accessibility and maintainability of the control system.

**Software**

**Processor Selection**

One of the most significant downsalls from the previous control systems was processor selection. The team worked to minimize development time by only using devices that members had used previously. In the end, this mentality cost the team. The system needed more flexible capabilities than could be provided by any of the individual boards. By competition, the system was comprised of a Raspberry Pi 3, a Teensy microcontroller, and a Mojo FPGA. Maintaining features between these three boards was a nightmare: a new sensor on the FPGA would require updates to the communications on the microcontroller and the Raspberry Pi. Although this system was too complex, the collage of chips clarified several of the capabilities the team wanted from the embedded system. The next chip would need to have programmable logic sections to support any peripheral CSM might need and at least a Linux operating system to provide a simple file system for data logging and networking.

**Network**

To improve the accessibility of the robots, the team needed to create a network system that would enable any member’s laptop to connect to and control the robots with ease. The team settled on the UDP protocol early in the design phase and focused on how to design extra features on top of the protocol.

**Design Review 2:**

The design of HERMES 4 became more solidified in the second design review; discussion focused on the component level of each subsystem. Early track tension and hopper flow test results were discussed in detail and further testing plans were presented. New tests were discussed to target any remaining perceived weaknesses in the conceptual designs. With the completion of the second design review, the team focused on finalizing the subsystems and moved into Phase C.

**Phase C: Final Design and Fabrication**

**Mechanical**

**Drive Base**

**Frame**

To maintain a reasonable weight, the team decided to use a redesigned frame constructed from aluminum tubing with larger cross sectional area. The new design replaced 1” diameter, 0.063” wall thickness tubes with 1.25” diameter, 0.083” wall thickness tubes. The increased tube size, along with a newly redesigned rigid geometry, provided a strong frame at a relatively low weight. Several machined components are utilized at major junctions to provide increased strength and precise location of critical mounting holes. After welding, the 6061 frames were heat treated to T6 properties to eliminate the risk of failure in the heat affected zone. A heat treat specific filler rod, AlcoTec ER4643, was used so that the welds would be able to achieve T6 strength.
**Drive Module**

As discussed in Phase B, the drive modules were redesigned to reduce the weight and physical size, and to increase the system’s dust tolerance. The final design of the drive module uses a 40V SL-MTI motor with a custom planetary gearbox. Three planetary stages are used: 9:1, 7:1, and 3:1, for a total reduction of 189:1. The planetary stages run inside of the final drive cog as shown in Fig. 6. The teeth of the drive cog have an involute profile specifically designed to interface with the track grousers. The gearbox features an integrated Trelleborg seal, and does not require any additional sealing. At operating speeds, the drive modules provide 57 N·m of torque at a ground speed of 0.42 m/sec. This light and compact gearbox was manufactured in-house apart from the ring gear, which was outsourced to a shop with wire EDM capabilities.

**Tracks**

The steel tracks used on HERMES 3 performed well and no major changes were required. Rather than altering the tracks, attention was focused on areas that needed improvement.

The tracks are automatically tensioned by the Dynamic Onboard Operational Tensioner (DOOT) system. The DOOTs consist of a small 12V motor and a custom temperature compensated strain transducer capable of monitoring and adjusting track tension continuously throughout operation. Continuous tension adjustment reduces the risk of belt slip or failure due to loose tracks, and eliminates some of the need for human maintenance. A DOOT schematic is shown in Fig. 7.

**Regolith Handling**

**Hopper**

The heart of the regolith handling system is the aluminum hopper. The hopper assembly consists of multiple 6061-T6 and 3003 aluminum sheet metal parts. The center plates are constructed from 0.125” 6061-T6 as these components carry significant loads and act as the interface between the hopper and the rest of the regolith handling system. The remaining hopper panels are 16 gauge (0.0508”) 3003 aluminum. By moving from 0.063” to 0.0508” thickness, the weight of each hopper was reduced by 0.70 kg, which translates to a total mass saving of 1.40 kg for a two-robot mining system.

The hopper design was improved by including a ten degree draft along the sides. The draft angle on the hopper allows regolith to flow freely from the hopper, improving the dumping efficiency of the system and decreasing the cycle time. During assembly of the hopper panels, rivets were installed so that the flat end of the rivet was located inside of the hopper. This small change helps to increase the ejection flow rate by removing an additional obstacle impeding the flow of regolith.
**Conveyor**

The center hopper panels also serve as the supports for the conveyor as shown in Fig. 8. The system consists of two side-by-side bucket ladder conveyors. Both belts are powered by a single Turnigy Aquastar motor with a 115:1 reduction gearbox. The gearbox uses two planetary stages and a single chain reduction stage, and is sealed inside of a machined aluminum dust cover.

The team intends to use the newly designed DCMBs on the digging conveyors. The DCMBs use the same involute profile as the track system, and allow CSM to take another step towards designing a space-ready system by removing the PVC belted conveyor that was previously used. The PVC belt is replaced with riveted ribbons of steel shim stock. The steel belt is three layers thick at any point, which adds redundancy to the system in case of failure at any individual ribbon. The steel shim belts reduce the weight of the conveyor system by 3.5 kg compared to the PVC belt. The conveyor system is tensioned using a third DOOT.

**Actuation**

The actuation system that lifts the hopper consists of a four-bar linkage and a Motion Systems Corporation 7” stroke internal feedback linear actuator. The actuator was modified to run with a Turnigy Aquastar motor, which is also used in the digging conveyor. The Motion actuator has a static capacity of 2200 N, which can be extended up to 8900 N for short duration events. The linkage was designed to keep the actuator force in its operating range throughout the mining cycle.

The individual linkage components are constructed from 0.125” 6061-T6 aluminum sheet metal. The linkage geometry was modified so that all the connection points were at end pins. This was done to remove the bending load that contributed to the HERMES 3 linkage failure. Hollow 4140 steel pins are used to connect the linkage members. Lock rings are used to secure the pins to minimize the risk of hardware binding with the hopper internals.

A positive stop was placed on the frame to decrease the axial loads carried by the linkage members during digging. When the hopper is lowered into the dig position as in Fig. 9, the back of the hopper rests against the positive stop. This allows the digging forces to be transferred more directly to the frame, rather than propagating through the linkage. When the hopper reaches its dig position, a limit switch on the positive stop is engaged, which signals the actuator to stop. The limit switch was added as an extra.
precaution to prevent damage to the frame in case the linkage would continue to lower the hopper past the positive stop. The addition of the positive stop will greatly increase the reliability and durability of the system.

**Electrical Integration**

CSM designed enclosures to protect electrical components from the environment and to increase system reliability. Made of 3003 aluminum sheet metal, the corners were welded together to provide strength and to seal the enclosures, preventing dust from entering. Fig. 10 shows the mounting location inside of the track. This design not only provides superior protection to electronics, but also improves stability by moving the center of mass down and forward.

Two additional cases were constructed. The first, housing the MicroZed and carrier board, was designed to allow bundled signals to be sent throughout the robot while originating from a central board. The second case houses the energy management system, the SMORE.

**Control**

**Hardware**

**Power Management**

For the final design, the team settled on a breakout board that would encompass the desired features for the power system. The SMORE includes many improvements over the previous design. The improvements are summarized in Table 3.

Table 3: Lists the notable features of the SMORE system

<table>
<thead>
<tr>
<th>SMORE Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage monitoring on all power rails</td>
</tr>
<tr>
<td>Current monitoring on each component</td>
</tr>
<tr>
<td>Pre-charging capacitors, to remove inrush current</td>
</tr>
<tr>
<td>Remote shutdown and power cycle capabilities</td>
</tr>
<tr>
<td>Short-term power supply for the 5V rail for emergency safe shutdown of the MicroZed</td>
</tr>
</tbody>
</table>

**MicroZed Carrier Board**

The main carrier board was completely redesigned for the MicroZed and new wiring system. The boards were designed in CircuitMaker and printed by Advanced Circuits. The new design designates I/O for specific purposes, whereas the 2016 design had generic peripheral connectors. These features are listed in Table 4.

Table 4: Lists notable features of the MicroZed system

<table>
<thead>
<tr>
<th>MicroZed Carrier Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two serial connections for motor controllers</td>
</tr>
<tr>
<td>Three 12V rails for the DOOTs</td>
</tr>
<tr>
<td>Six high-power LED drivers</td>
</tr>
<tr>
<td>5V GPIO outputs to drive the status LED’s</td>
</tr>
<tr>
<td>Voltage dividers for each rail</td>
</tr>
</tbody>
</table>

**Wiring**

The wiring system was also redesigned this year, with the main board breaking out all connections to high density D-sub connectors outside of the carrier case. The D-sub connectors were chosen because they offer high reliability, secure connections, high current, and are commonly available in dust-proof variations. An additional benefit of these connectors is their locking mechanism reducing the risk of wires being...
unplugged. Finally, the team chose to put male connectors onto the cases because their geometry would allow for easier dust removal from unused connections.

**Sensing**

*Location Sensing*

The telemetry system primarily uses decawave DWM1000 modules, which are capable of performing time-of-flight ranging between each other with an accuracy within ±4”. The control and calculations are done on a separate ARM processor. Each of the processors also takes in data from the MPU9250 inertial measurement unit (IMU) on the same board, and combines them with a Kalman filter. The combination of a very precise but inaccurate IMU and very accurate but imprecise time-of-flight modules allows the telemetry system to achieve both high accuracy and precision.

*Regolith Sensing*

HERMES 4 utilizes both volume and mass detection. Both systems are desired because of the variation of density between BP-1 and icy regolith. A series of photocells and high-power LEDs are mounted on opposite sides of the interior of the hopper. By finding the point at which the photocells transition from light to dark, the robot estimates the volume of regolith in the hopper. Readings from a series of strain gauges on frame members around the hopper are also combined with the current angle of the hopper to measure the weight of regolith in the hopper. The combination of these two systems allows the robot to stop before it reaches either of its limits.

*Track Tension and Frame Strain*

The DOOTs utilize strain gauges to measure tension in the tracks. The strain gauges are arranged in a full bridge pattern to reduce the thermal effects and improve resolution. To measure the output voltage of Wheatstone bridges on the robot, the team uses the HX711 chips, which feature 24-bit ADC’s and send a digital representation of the strain to the main carrier board.

**Power Sensing**

The SMORE can monitor power in every component, and uses this feedback to estimate battery capacity remaining, calculate efficiency, and detect stalls. The current sensor data are also sent to the MicroZed for logging. These data are used to add current limiting to the Aquastar speed controllers. A block diagram of the power system can be found in Appendix B. The diagram denotes what the SMORE encapsulates.

**Software**

*MicroZed*  

The MicroZed development board was chosen to replace the Raspberry Pi used in previous systems. The decision was made to centralize embedded control and development. The MicroZed has both an ARM processor and a sizeable FPGA. These increased capabilities enable the development of digital modules to interface with the various sensors, motors, and other processors on board.

**Network**

This year, the software developers implemented a UDP system. The final protocol adds an optional acknowledge to datagrams, allowing critical messages between the application and the robot to be guaranteed. The protocol also supports server discovery, a feature fully realized by a server browser in the main page of the Windows application. These features allow anyone with a Windows computer to quickly connect and begin controlling the robots. The network code uses two layers of message. The lower layer is called the datagram layer. For the CSM network, datagrams establish and maintain connections, broadcast server queries, and acknowledge mandatory datagrams. The application layer uses packets, which are carried by datagrams. A packet can be flagged as mandatory so that both the robot and client recognize its reception before moving
on. Non-mandatory packets are treated as a stream; the only information that matters is the most recent. Fig. 11 outlines the organization of these datagrams and packets.

![Figure 11: Communications diagram; Packets are shaded green and datagrams are shaded in blue.](image)

**Windows Application**

The Windows application serves as the user interface for controlling the robots. The application was written in C# using WinForms in Visual Studio. The application implements the networking protocol and provides an easy-to-use interface for anyone to control the robot and view sensor information. The application gets driver input from an Xbox controller to control the robot. It also provides the user with an easy menu to switch between disabled, manual, and autonomous states and jump to any point in the autonomy flow chart. For sensor display, the team made a map of the field that can plot both robots on it.

When each robot reports its location and orientation, the robot is drawn on the map to show the driver. The goal of visual representation is to reduce the team’s dependence on cameras. All telemetry data from sensors are logged to a text file and graphed for the driver in the application. The application also logs each network packet and user message for debugging. A screenshot of the application can be found in Appendix B.

**Autonomy**

**Strategy**

To prevent collision and maintain simplicity, CSM treats each robot as its own autonomous system that follows its own path by splitting the arena into halves. There are eight possible starting orientations for the two-robot system. Upon start up, each robot identifies its location and its orientation, horizontal or vertical. If the robots are stacked horizontally, the leftmost robot mines the left half and the other robot mines the right. If the robots are stacked vertically, the robot furthest from the hopper mines the starting side, and the robot closest to the hopper mines the opposite side. Once the mine zones are identified, the robots separate, rotate, and drive accordingly so that they are aligned with their mining zones. These steps are visually represented in Appendix B under Path Alignment. After the robots align themselves with their respective mining zones, the mining cycle in Fig. 12 begins.

The cycle contains five basic steps that are repeated until the allotted competition time is over. A more detailed logic flowchart is available in Appendix B. The first step is for the robot to navigate toward its desired location. To achieve this goal, the robot sets a target and drives toward it. During its path to the target, it continually checks to make sure it is pointed at the target. If the difference between the present path and its desired path is outside of a predetermined threshold, it corrects its orientation. As shown in Appendix B, under the Navigation header, the path of the robot can be broken down into four target locations with three segments linking them together. Additionally, for each mining cycle the robot varies its mining location horizontally. Once the robot reaches the desired mining location, it begins to mine. First, it turns on the conveyer and lowers it into the regolith. Next, it slowly drives forward until the maximum carrying capacity has been reached or it
drives too close to the arena wall. When the robot hopper is determined to be full, the robot stops driving, turns off the conveyer, and raises it to the transit position. Lastly, the robot reverses to the collection bin along the same path it came. While approaching the collection bin and driving into the dumping zone, the robot confirms the location of the second robot; only one robot will occupy the dumping area at a time. Next, it drives directly in front of the collection bin and aligns itself using lasers. This is accomplished by rotating until the light from the lasers bounce off of retroreflective tape back to the robot. Finally, the robot dumps all the material from the hopper and repeats the cycle.

**Sensor Application**

Successful autonomous operation requires a digital awareness of the robot states. To do this, CSM needs to apply the sensor systems appropriately. The two challenging states for each robot to track are location and amount of collected material.

For location, the robots rely heavily on the telemetry system. Unlike dead reckoning, telemetry does not drift over time, so it can reliably gauge the position of the robots without any error caused by sliding. During autonomy the telemetry system is used to verify location and determine when each bot has traveled far enough to begin legally mining.

For mining detection, the autonomy process uses the mass and volume detection systems. Together, the photo-resistors and the strain gauges provide an accurate measure of the mined material. However, during mining, the digging forces create additional stresses that are not distinguishable from strain due to loading. To counter this, the autonomy correlates the mass collected with the distance mined. The distance and amount collected should be fairly correlated and can be assessed while mining.

**Fabrication**

The bulk of fabrication took place in on-campus labs. In addition to standard hand and woodworking tools, CSM has access to a wide range of power equipment including CNC and manual mills, lathes, a waterjet, and sheet metal forming tools.

Some work was outsourced in the interest of time and accuracy. The frame tubing was coped and CNC bent by VR3 Cartesian, a performance race frame manufacturer in Quebec. Hopper panels and electrical enclosures were laser cut and CNC bent by CSM sponsor ALMACO, an agricultural products manufacturer in Iowa. By outsourcing these jobs to experienced manufacturers, the team could create more robust designs without worrying about the tolerance issues often introduced by hand bending.

To ensure the timely completion of the fabrication stage, CSM relied on strong communication and manufacturing fallback plans. The team is currently on track to complete all manufacturing and assembly on time, but fallback plans exist in case there is a delay for any individual component.

**Design Review 3:**

The final design review was a complete summary of every subsystem that had been designed. The design was in its final state, but sufficient time remained to implement additional changes if any significant issues were identified. Team leaders presented their individual subsystem designs and discussed the interfaces between the systems. Several prototype models were shown along with the CAD designs. The team reviewed the goals and action items generated during the first and second design reviews to ensure
that all concerns had been met. At the end of the review, approval was given to begin placing major stock orders and to begin manufacturing and assembly of the robots. Assembly began and the team progressed to Phase D.

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

**System Assembly Overview**

As soon as all three frames were completed, assembly of the test robot began. The test robot will be completely assembled and checked for any potential issues or inefficiencies to guarantee that both competition robots are in the best possible condition. First, the frame was acquired and checked for dimensional accuracy. Then, the control team set up all power wiring and component wiring. Completing all necessary wiring first ensures that a minimum amount of wires are exposed or in high risk areas of the robot. Going forward, all components including the hopper, excavation system, and track system will be installed on the test robot. Upon completion of the assembly process, testing will begin.

**Completed Testing**

Math models for each subsystem are being finalized while robot assembly is being completed. Upon assembly completion, each subsystem will be individually tested in a custom-built testing chamber using a specialized regolith simulant. The results will then be compared to the ideal values given by the math models. Additional investigation and modifications will be made if actual values deviate significantly in comparison.

**Simulant Creation**

Due to the unique behavior of BP-1, testing in common materials like sand is not recommended when evaluating how a robot will perform during the competition. This, combined with the necessity of testing and verification, led to the creation of a specialized testing arena with a more accurate simulant.

In a previous year, a member of Cyclone Space Mining obtained a sample of BP-1 from NASA and was able to take data from that material to base a simulant off of. The material was found to have a shear angle of roughly 85 degrees. Sand was initially considered to be used for testing due to its abundance, but it was found that even when density was similar, the highest consistent shear angle was around 30 degrees, well below the 85 degrees of BP-1. Eventually a combination of Portland cement, fly ash, and fine sand, mixed in a 5-3-1 ratio by weight, produce a nearly identical shear angle and density [3].

**Test arena construction**

In previous years, CSM had access to a simulated mining arena. Due to campus expansion efforts in 2016, CSM was forced to relocate and lost access to the testing arena. Although this event caused the team to lose valuable testing time, it also presented an opportunity to expand testing capabilities. A new testing arena was designed that featured a section with icy regolith simulant, allowing future members to explore icy regolith collection strategies. The arena is still under construction; upon its completion on May 3rd, testing will resume.

The testing arena was designed to allow members to observe both excavation and locomotion testing. Due to the hazardous nature of the developed simulant, several safety requirements were also taken into consideration. A ventilation system was installed to keep the room at a negative pressure to prevent any simulant from leaving while personnel are entering and exiting. Those entering the chamber containing the simulant must also be outfitted in a hooded coverall, nitrile gloves that have been sealed with duct tape, goggles, and a reusable respirator.

**Track Tensile Test**

The new steel shim stock belts, while much lighter, pose a risk of breaking due to tensile loading. A section of the track was placed in a tensile tester and pulled along the length of the shim stock. Under worst
case scenario loading, the math model predicted a tensile force of 1300 N. The data showed a maximum tensile strength of 1500 N. These values were used when determining the necessity of obstacle avoidance and maximum allowable acceleration.

**Tensioner Testing**

The DOOT track tensioners rely on a purpose-built Wheatstone bridge strain transducer for sensing. Due to the impact that temperature swings can have on material strain, the difference between Iowa and Florida climates was a concern. To confirm the temperature compensation properties of a full Wheatstone bridge, the DOOT system was placed into a cooler for approximately 12 hours and then used. When the same amount of force was applied to the cooled system it gave an identical reading as when the system was at room temperature, confirming that the system had compensated for a temperature difference of 40 degrees Fahrenheit without issue.

**Risk Mitigation Plan**

The nature of regolith mining brings many risks to the functionality of the robotic mining system. CSM has outlined the pertinent failure modes associated with these risks in the DFMEA located in Appendix A. Certain actions are established in the case of a failure mode occurring during testing, practice, or competition. In the incident of a mission failure type event, replacement parts can be obtained from the HERMES 4 practice robot or repurposed from the HERMES 3 robots. Any threats to mission success can be mitigated through proper verification of system performance. A list of planned system verifications tests can be found in Appendix A and are scheduled to occur before the competition. Another category of risk to the project would be failure of completion due to lack of time or funds. While the possibility of this failure is unlikely due to increased efforts in scheduling and project management, plans are in place to reduce its severity. The team is assembling a practice robot before the two competition versions. The practice robot can be used to replace a competition one if necessary. A $5000 contingency fund has been set aside for future years or the need for expensive replacement parts. CSM can also rely upon competing with a single robot system as a worst case scenario since each robot contains all necessary functions for the competition.

**Resource Management**

**Financial Budget**

CSM’s budget is divided into mechanical and control categories. The budget and estimated costs are derived from the costs of previous robots. Actual robot costs are the out-of-pocket expenses incurred by the club. Expenses shown in Table 5 are current as to the submission date of the report and are in line with what was expected.

**Table 5: Budget plan with estimated costs and cost to date**

<table>
<thead>
<tr>
<th>Systems</th>
<th>Allocated Budget (Both Robots Combined)</th>
<th>Estimated Cost</th>
<th>Cost To Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Systems</td>
<td>$12,000.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw Stock</td>
<td>$2,000.00</td>
<td>$1,845.00</td>
<td></td>
</tr>
<tr>
<td>Fabrication/Tooling</td>
<td>$3,000.00</td>
<td>$1,485.00</td>
<td></td>
</tr>
<tr>
<td>Components</td>
<td>$4,000.00</td>
<td>$3,015.00</td>
<td></td>
</tr>
<tr>
<td>Testing &amp; Development</td>
<td>$2,000.00</td>
<td>$1,650.00</td>
<td></td>
</tr>
<tr>
<td>Drive Train</td>
<td>$500.00</td>
<td>$500.00</td>
<td></td>
</tr>
<tr>
<td>Controls &amp; Electrical</td>
<td>$7,000.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development Hardware</td>
<td>$1,750.00</td>
<td>$1,225.00</td>
<td></td>
</tr>
<tr>
<td>Power System</td>
<td>$1,100.00</td>
<td>$1,250.00</td>
<td></td>
</tr>
<tr>
<td>Communications</td>
<td>$600.00</td>
<td>$435.00</td>
<td></td>
</tr>
<tr>
<td>Connectors and Cables</td>
<td>$2,300.00</td>
<td>$2,015.00</td>
<td></td>
</tr>
<tr>
<td>Control Boards</td>
<td>$1,100.00</td>
<td>$860.00</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$19,000.00</strong></td>
<td><strong>$18,350.00</strong></td>
<td><strong>$14,280.00</strong></td>
</tr>
</tbody>
</table>

Numbers Rounded to nearest whole number.

**Mass Budget**

Per NASA RMC guidelines each kilogram of weight of the robot translates to negative points in the competition [4]; a successful RMC participant must optimize the performance of a subsystem against its added weight. Shown below in Table 6 is the estimated weights of each subsystem. This mass budget allows the team to identify subsystems that could benefit from mass reduction.
Power Consumption Estimates

Power management for the HERMES 4 system was redesigned to allow better monitoring and control of power throughout the bot. Table 7 shows expected power consumption for one robot during a full 10-minute competition run. With an expected regolith collection of 250 kg per robot, the ratio of collected regolith to power consumed for one robot was found to be 6.23 kg/Wh.

Data Budget

The data budget shown in Table 8 is based on expected operation of the team’s network protocol. The estimated rates assume a minimum ethernet frame of 64 bytes with actual UDP, IP, and Ethernet overhead of 46 bytes. The rates are driven by the embedded and Windows applications and may be adjusted after further testing.

Table 7: Power Consumption Estimates for one robot during a 10-minute competition run

<table>
<thead>
<tr>
<th>CSM 2017 Power Consumption Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
</tr>
<tr>
<td>--------------------------------------</td>
</tr>
<tr>
<td>Orienting robot to field (only done at start)</td>
</tr>
<tr>
<td>Traveling to mining location</td>
</tr>
<tr>
<td>Lowering hopper</td>
</tr>
<tr>
<td>Mining</td>
</tr>
<tr>
<td>Raising Hopper</td>
</tr>
<tr>
<td>Returning to starting location</td>
</tr>
<tr>
<td>Orienting with dump zone</td>
</tr>
<tr>
<td>Raising Hopper to dump</td>
</tr>
<tr>
<td>Lowering hopper</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

Table 8: Estimated data consumption during autonomy and manual modes operation

<table>
<thead>
<tr>
<th>Autonomous Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Destination</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Robot</td>
</tr>
<tr>
<td>Application</td>
</tr>
<tr>
<td><strong>Total Kb/s</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Manual Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Destination</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Robot</td>
</tr>
<tr>
<td>Application</td>
</tr>
<tr>
<td><strong>Total Kb/s</strong></td>
</tr>
</tbody>
</table>

Conclusion

During the 2016-2017 NASA RMC competition year, Cyclone Space Mining has implemented a series of improvements to develop a highly capable robotic mining system. Each innovation was driven by the need to solve the leading issues of the previous design. The new system has progressed specifically in the areas of reliability, durability, accessibility, and maintainability. Additional attention in the design process was also invested towards testing capabilities and time management to promote a better systems approach. Once verification of the system meeting all requirements and mission goals is complete, HERMES 4 will be ready for launch at the 2017 NASA RMC. The team hopes that NASA will find the new design to contain useful applications towards actual ISRU missions in the future.
References


Appendix A – DFMEA and Verification Plans

### Cyclone Space Mining Robotic Mining Competition DFMEA

<table>
<thead>
<tr>
<th>Item/Function</th>
<th>Potential Failure Model(s)</th>
<th>Potential Effects</th>
<th>Root Cause</th>
<th>Design Controls</th>
<th>DET R PN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotion</td>
<td>Robot tips</td>
<td>Mission failure</td>
<td>8</td>
<td>Center of mass surpasses base</td>
<td>2</td>
</tr>
<tr>
<td>Frame members and connections</td>
<td>Yielding or fracture</td>
<td>Threat to mission success or Mission failure</td>
<td>8</td>
<td>Tensile forces on members are too great</td>
<td>4</td>
</tr>
<tr>
<td>Motor</td>
<td>Motor burns out</td>
<td>Mission failure</td>
<td>8</td>
<td>Excessive torque on motor output shaft causing high voltage or amperage</td>
<td>2</td>
</tr>
<tr>
<td>Motor</td>
<td>Components of gear box degrade</td>
<td>Mission failure</td>
<td>8</td>
<td>Regolith degrades components or repeated wear weakens components</td>
<td>3</td>
</tr>
<tr>
<td>SCMB Conveyor or SCMB Track</td>
<td>Belts slip off of drive cog</td>
<td>Mission failure</td>
<td>8</td>
<td>Belts lose tension</td>
<td>4</td>
</tr>
<tr>
<td>SCMB Conveyor or SCMB Track</td>
<td>Fracture</td>
<td>Threat to mission success or Mission failure</td>
<td>8</td>
<td>Forces within the belt surpass the limits of the material</td>
<td>5</td>
</tr>
<tr>
<td>Controls</td>
<td>Disconnected wires</td>
<td>Mission failure</td>
<td>8</td>
<td>Jostling of robot causes wires to disconnect</td>
<td>3</td>
</tr>
<tr>
<td>Controls</td>
<td>Software bugs</td>
<td>Exact effect unknown, potential to cause mission failure</td>
<td>8</td>
<td>User error during programming</td>
<td>4</td>
</tr>
<tr>
<td>Controls</td>
<td>Autonomy malfunction</td>
<td>Loss of autonomy points</td>
<td>6</td>
<td>Sensor malfunction, orientation loss</td>
<td>5</td>
</tr>
<tr>
<td>Controls</td>
<td>Communication Failure</td>
<td>Threat to mission success</td>
<td>8</td>
<td>Packet loss, power shortages, or poor connection</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Watchdog timer to start reconnection</td>
<td>1</td>
</tr>
</tbody>
</table>

### Verification Plans

#### Minimum Functionality Verification.
- Run robot in simulated environment for 10 minutes without failure.
- Run robot with full load in simulated environment for 10 minutes without failure.
- Observe robot’s ability to traverse obstacles with and without material in hoppers.

#### Excavation Systems Verification.
- Test hoppers’ built in mass detection systems in order to ensure accuracy.
- Record time required in order to fill hoppers depending on dig depth.
- Record time required in order to empty hoppers depending on dump angle.
- Perform dump angle test before and after applying an anti-stick coating, SlipPlate, to inside of hoppers in order to determine the necessity of said coating.

#### Actuating System Verification.
- Fill hoppers with 75 kg of material, 20% over typical maximum mass, and cycle hoppers up and down 10 times without failure.

#### Electronic Systems Verification.
- Run robot autonomously in simulated environment in order to confirm its ability to navigate without assistance.
- Develop and implement a training program that will ensure our control team is capable of manually operating the robot.
Test Plan # 3

Test Name: Track Tensile Test
Test Date: 10/22/16
Project Manager: [Signature]
Test Lead: [Signature]

Test Information

Objective of Test: To determine the strength of the steel shim stock tracks in tension. Compare to maximum estimated tension from math model.

Test Location and Environment:
Black 1070 (lab room)

Tools Required:
Universal Testing Machine (Tensile Tester)

Special Testing Requirements:
None

<table>
<thead>
<tr>
<th>Step</th>
<th>Test Steps</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fit 3 small track sections with metal holding pieces on either end</td>
</tr>
<tr>
<td>2</td>
<td>Run 3 samples in tensile tester until yield</td>
</tr>
<tr>
<td>3</td>
<td>Record maximum force at yield</td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Test Results

Acceptance and Failure Criteria: The math model predicts a maximum tensile force of 1500 N for a worst case scenario. This is compared to the yield strength of the track.

Summary of Results: The average maximum tensile strength of the track was 1500 N. One sample was not considered as the holding mechanism was faulty.

Test Lead Recommendations: I recommend that the tracks are safe and be used.

Project Manager Recommendations: I agree with Will's recommendation. We should move forward with steel shim tracks, but should do further testing for conveyer.

Test Data Storage Location: Lunabotics Drive: \Lunabotics 2016-2017\Testing
Appendix C – Gantt Chart

Cyclone Space Mining

NASA RWC at Kennedy Space Center, Florida