UNIVERSITY OF COLORADO - BOULDER

ASEN 4028 - SENIOR DESIGN II

Project Final Report

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List of Acronyms

- **GOPHER**: Ground Operations for Precise Harvesting and Extraction of Regolith
- **FBD**: Functional Block Diagram
- **PCB**: Printed Circuit Board
- **CAD**: Computer-Aided Design
- **PVC**: Polyvinyl Chloride
- **FEE**: Fundamental Earth Moving Equation
- **ISRU**: In-Situ Resource Utilization
- **FBD**: Free Body Diagram
- **PLA**: Polylactic Acid
- **DMM**: Digital Multimeter
- **GUI**: Graphical User Interface
- **PID**: Proportional-Integral-Derivative

Nomenclature

- **mm**: Millimeter
- **cm**: Centimeter
- **m**: Meter

- **g**: Gram
- **kg**: Kilogram
- **s**: Second
- **A**: Ampere
- **N**: Newton
- Nm: Newton Meter
- **Pa**: Pascal
- **W**: Watt
- **Hz**: Hertz
- **V**: Volt
- Ω: Ohm
- **rpm**: Revolutions Per Minute
- V_{in}: Voltage In
- V_{out}: Voltage Out

1 Project Purpose and Design

1.1 Field of Application

Future missions to celestial bodies, such as the Moon, necessitate advanced capabilities for mining and excavation to facilitate scientific exploration. The prospect of mining on the lunar surface introduces a number of complex engineering challenges. The primary objective of this project is to develop a robot capable of mining regolith in a simulated off-world settings. The project focuses on creating small, stationary robots designed to be deployed by a mother rover to specific locations on lunar terrain. Operating in harsh and inhospitable environments unsuitable for human presence.

The overarching mission involves a ground station commanding a mother rover and stationary digging robots. The mother rover drops the digging robots at designated locations to harvest regolith. The mother rover subsequently collects the harvested regolith and digging robots before returning to the base.

1.2 Problem Addressed

Operating in harsh and variable lunar environments unsuitable for human presence poses significant engineering challenges. The core problem this project addresses is the development of autonomous, efficient mining capabilities on the Moon. The robots are designed to remain stationary, overcoming the complexities of lunar surface conditions, and are capable of excavating through layers of regolith and rocks without moving , which would consume substantialy more energy.

1.3 Benefits of a Successful Project

Due to the projects successful completion, it is expected to offer several significant benefits:

1. **Contribution to Lunar Exploration Technologies**: The demonstration of new techniques and methodologies for robotic mining will add to the evolving field of lunar technology.
2. **Proving a Stepping Stone for Future Developments**: Creating a terrestrial prof of concept will move forward. The ability to harvest lunar regolith efficiently. Which is crucial for long-term lunar missions for reducing the dependence on Earth-supplied resources.
3. **Education and Learning**: This project provided the team a unique opportunity to develop both our engineering, communication, and teamwork skills.

In essence, the successful implementation of GOPHER has demonstrated an effective robot with a unique design, and hopefully add to a foundation for further development to its design or similar projects, both within the university and the Aerospace community.

1.4 Driving Requirements

Req. Number	Description
0.0.4	The digger shall be capable of operation for at least 10 cycles.
1.1.3	The digger shall maintain a stationary position on the surface of the environment.
1.1.4	The digger shall accept start, stop, and sleep commands from the ground station.
1.2.1	The digger shall harvest a total of 0.5 kg of regolith material per 15-minute dig cycle.
1.2.2	The digger shall operate and perform digging operations to harvest regolith (simulated as gravel) that is buried below a 2 cm layer of sand.
1.2.3	The digger shall be able to harvest regolith when larger rocks (5 to 8 cm in diameter) may be interspersed.

1.5 Concept of Operations

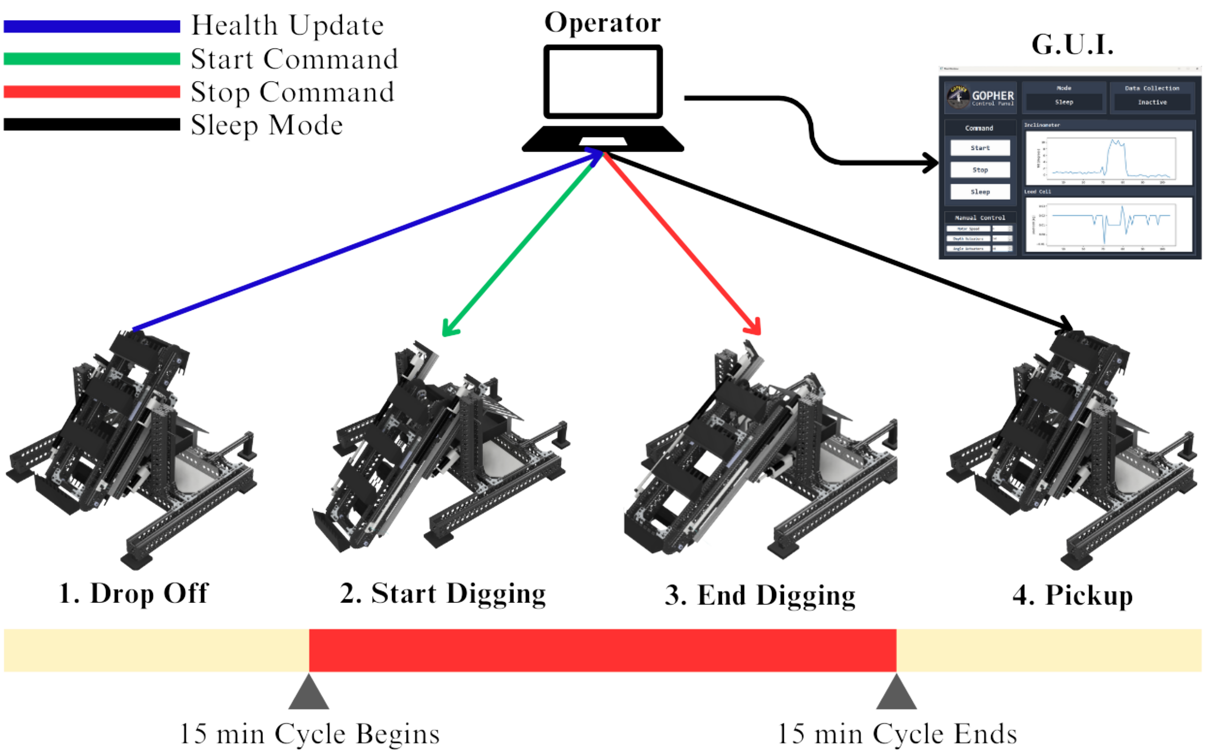

Figure 1: Con Ops

Introduction: The GOPHER digging robot is designed for material excavation in controlled environments. It operates in a four-phase cycle, designed for the extraction of simulated regolith.

Phase 1 - Deployment and Initial Assessment: GOPHER's operation begins with its manual placement and activation in the environment. The placement is performed by a human operator. After being turned on it uses an onboard accelerometer to evaluate ground slope, ensuring compliance with a ±5-degree grade. If the accelerometer determines that the grade is greater than the requirement it sends a reposition request to the operator. If conditions are satisfactory, GOPHER enters standby, awaiting a start command.

Phase 2 - Beginning of Digging Cycle: Upon receiving the start command, GOPHER commences a 15-minute digging cycle. The cycle may terminate for two reasons: successful collection of 0.5 kg of regolith or reception of a stop command from the operator.

Phase 3 - End of Digging Cycle: This phase marks the end of the excavation activities, triggered by one of the previously mentioned termination conditions. It signifies the completion of GOPHER's primary operational task.

Phase 4 - Sleep & Shutdown: In the final phase, GOPHER retracts its digging apparatus to return to its initial size configuration and powers down all non-essential systems, including sensors and actuators. The robot then enters a low-power sleep mode, awaiting manual shutdown and subsequent retrieval.

1.6 Functional Block Diagram

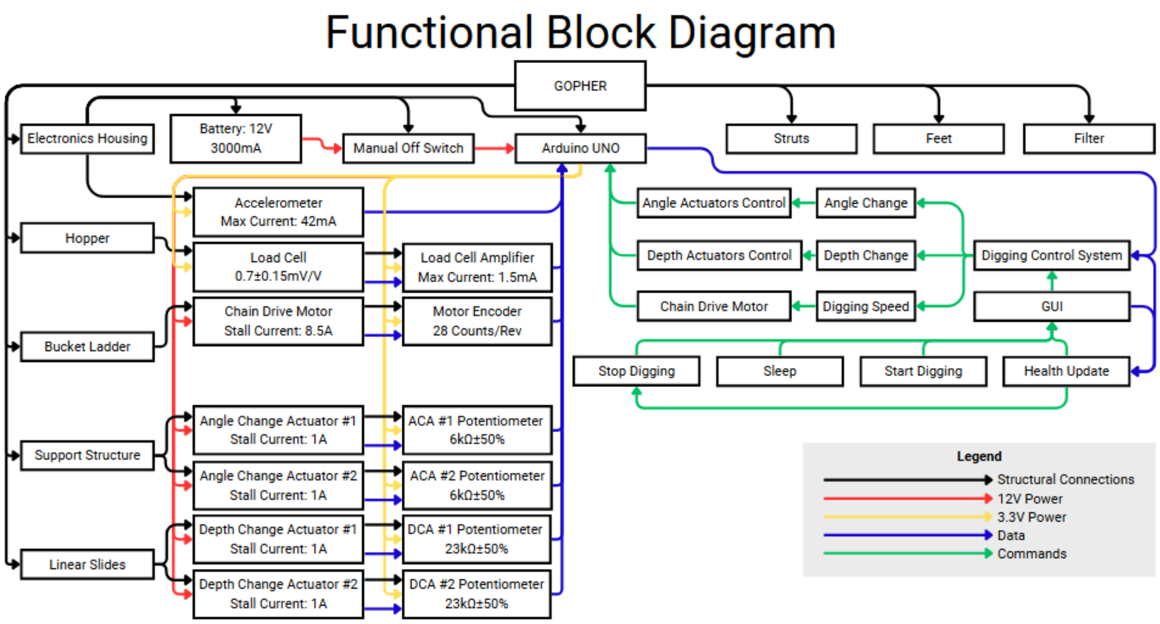

Figure 2: FBD

Overview: The GOPHER FBD displays the relevant subsytems and their connections, including structural connections depicted by black lines, and power supplies categorized into 12V and 3.3V represented by red and yellow lines, respectively. It also features blue lines for data connections and green lines for command signals. The structural framework includes non-electronic components such as feet, struts, and a filter. The hopper section of the robot is equipped with a load cell connected to an amplifier, with a 42 mA current at 3.3V and a data rate of 80 Hz. The bucket ladder is powered by a REV HD Hex Motor with a Magnetic Encoder, requiring 12V for the motor and 3.3V for the encoder. Additionally, the digging mechanism consists of four Actuonix P16-P Actuators with built-in Potentiometers, necessitating 12V for the actuators and 5V for the potentiometers. The software subsystem controls digging operations via Start, Stop, and Sleep commands. In terms of construction, the robot primarily utilizes off-the-shelf parts, with certain components like the feet, hopper, and filters being 3D printed.

1.7 Design Description

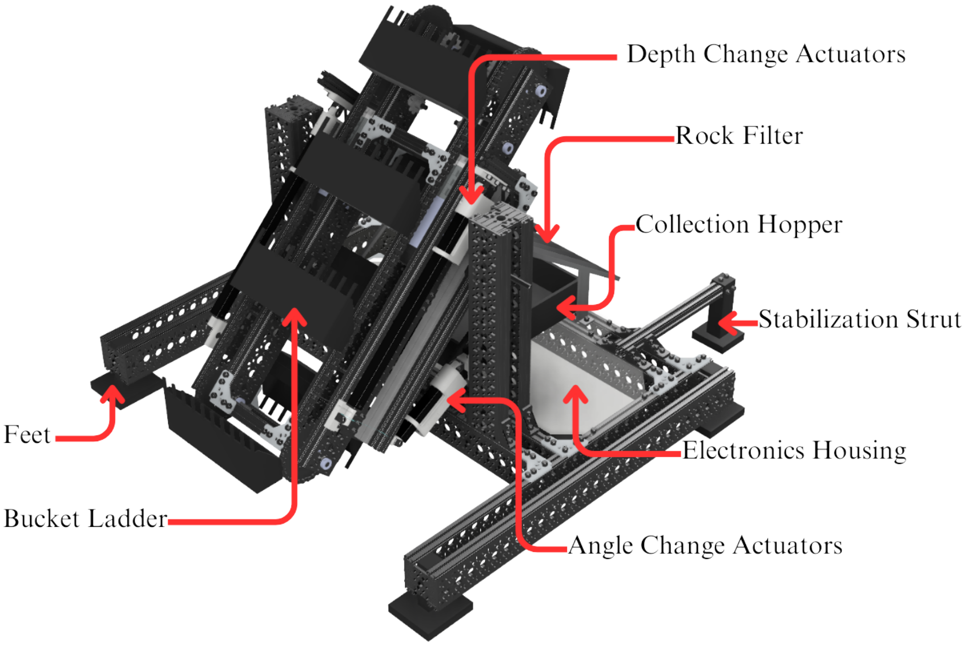

Figure 3: GOPHER CAD Front View

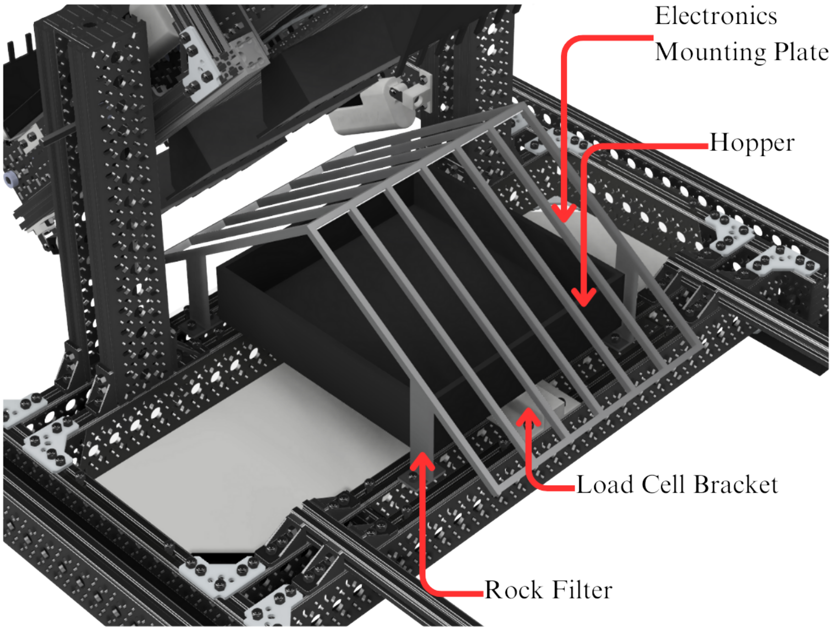

Figure 4: GOPHER CAD Rear View

1.7.1 High Level-Design Explanation

The GOPHER system is an integrated assembly consisting of four primary subsystems: the digging system, the main structural framework, the material collection system, and the electronics system. These subsystems are designed to function cohesively, optimizing the processes of digging and material collection for aerospace applications.

The structural framework of the GOPHER system is built using commercially available aluminum C-channel, chosen for its optimal balance between strength and weight. This main structure is supported by four feet and external stabilization struts to prevent tipping during operations, emphasizing stability in varying operational conditions.

Within the main frame, the electronics are compactly housed between the aluminum C-channels. This configuration protects the electronic components while ensuring compactness and maintenance efficiency. The electronics are mounted on an acrylic base plate and are further protected by an additional acrylic top plate, which safeguards against environmental factors. Above this top plate, a load cell mount attached to a hopper is installed for the weighing of collected materials.

A filter positioned above the hopper ensures that larger rocks are excluded from the collection process, thereby enhancing the quality and consistency of the samples collected. The operational mechanism of the GOPHER is centered around the Bucket ladder system, which is powered by a single motor. This system features buckets that move along a chain, digging through the environment and delivering materials to the hopper.

The digging capabilities of the system are augmented by two linear actuators, one on each side, that extend the bucket ladder system into the ground. An additional pair of actuators are employed to adjust the angle of the entire digging system, thereby extending its digging capabilities and enhancing its adaptability to varied terrain conditions.

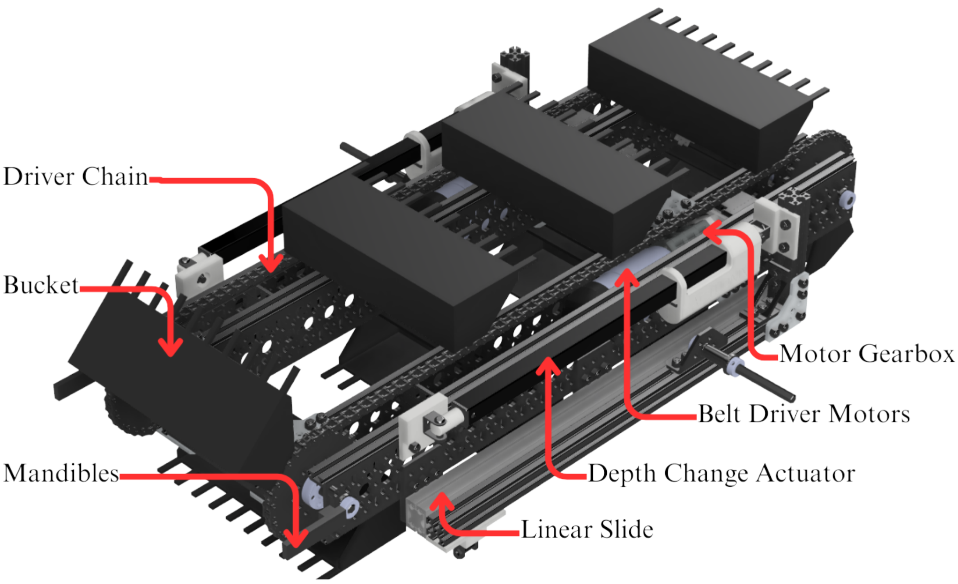

Figure 5: Digging System CAD

1.7.2 Digging System

The digging system is engineered around a chain-driven mechanism, powered by a REV HD Hex motor. This motor, essential for robust operations, is connected via a 12V 2-pin power connector, ensuring adequate power supply. Additionally, it features a 3.3V four-pin magnetic quadrature encoder. A key component of the motor assembly is the 60:1 gearbox, which significantly increases the motor's torque from 0.105 Nm to 6.3 Nm. This increase is crucial for the digging system's operation, allowing it to penetrate tough materials efficiently while not providing enough toque to tip the system if the digger encounters unexpected resistance.

Adjustments for digging depth and angle are facilitated by Actuoix P16-P linear actuators. These actuators are specifically chosen for their reliability and performance, with the depth change actuators providing a 200 mm stroke, and the angle change actuators offering a 50 mm stroke. The system is capable of achieving a maximum digging depth of 12 cm, with variable angle adjustments for versatile operational capabilities. Each Acatuaro can applie 100N of toque and can handle 200N of backforce.

Control of the digging system is maintained manually by the operator, who adjusts the stroke length of the actuators and modifies the digging motor's speed based on the requirements of the task. This manual control allows for precise modifications in real-time, adapting to varying environmental conditions.

1.7.3 Electrical

The electronic system of the project is composed of several interconnected subsystems, centrally managed by an Arduino Uno REV3. This controller serves as the heart of the system, orchestrating operations across multiple components. It is connected through digital connections to four accelerometer control boards from Actuonix, known as LAC Controls. These boards are independently powered and equipped with internal control systems that process inputs from the potentiometers on the actuators.

Power for the various electronic components is supplied by a REV 12V 3000mAh battery. This battery is linked to the rest of the system via a manual on/off switch and distributes power through a breadboard, which efficiently manages and allocates electrical flow to the various subsystems.

The motion of the motor is regulated by a REV motor driver REV3, ensuring precise control over its operations. Additionally, the system integrates an accelerometer, which is connected to the Arduino to provide accurate angle readouts essential for preventing tipping. The load cell's measurements are managed by a SparkFun Qwiic Scale - NAU7802, a digital convert that then feeds the data signal into one the Arduino digitial pins.

1.7.4 Software

The software subsystem is designed to control and monitor the operations of the GOPHER system. Interaction between the operator and the GOPHER is facilitated through a Graphical User Interface (GUI), the layout of which is depicted above. The GUI includes essential controls such as start, stop, and sleep buttons. The start button initiates the system, the stop button ceases the activity of the digging motor, and the sleep button retracts the GOPHER to its initial position before shutting down its systems.

Manual control within the GUI encompasses three main commands that govern the GOPHER's primary movements. The first control adjusts the motor speed, which is set in intervals ranging from zero to 255, although the motor only activates when the input reaches a minimum of 150. The second manual control manages the depth change actuators, accepting input values from 0 to 200, which correspond to the stroke length of the depth change actuator in millimeters. The third control pertains to the angle change actuator, which accepts values from 0 to 50, matching its maximum stroke length of 50mm. These actuators are coordinated by simple control loops to ensure synchronous extension and retraction.

The software also interfaces with two critical sensors: the accelerometer, which is directly connected to the Arduino, and the load cell. These sensors provide live readouts on the GUI, updated every second. This real-time feedback is vital for the operator to monitor the system's performance continuously and to verify that the target of 0.5kg of regolith has been successfully collected. This setup ensures precise control and instant feedback, essential for efficient operation and successful mission outcomes.

2 Testing, Verification, and Validation

2.1 Introduction

The GOPHER adopted a thorough testing approach, focusing on verification and validation of all requirements to ensure a seamless design and final product. GOPHER requirements were verified primarily by testing. Each test was designed such that its success criteria verifies at least one requirement.

Test	Description	Req.	Equipment	Location	Completed?
Component Level					
Mechanical					
Scoop Filtering	test that the scoop can filter out sand through the slots of the scoop.	2.1.1	Sand	Sandbox	Complete [Pass]
Scoop Teeth Strength	test scoop teeth strength by scooping against the densest rocks provided. Test 3-D printed PLA material to visually see if it is quickly degrading and if metal scoops are neccessary.	2.1.2	Rocks	Sandbox	Complete [Pass]
Regolith Ramp Filtering Accuracy	test that large rocks will not filter through the ramp while small rocks will filter through with no jamming.	1.2.3, 0.2	Rocks	Sandbox	Complete [Pass]
Electrical					
Motor Aliveness	test that motors power on/off. Power the motor encoders to verify voltage output with DMM is the same levels expected as the data sheet.	1.2.2	DMM, Power Supply	Electronics Lab	Complete [Pass]
Motor Max Current	test that fuse implemented into motor will shut off power supply to motor before current reaches the stall current.	0.3	DMM, Power Supply	Electronics Lab	Complete [Pass]
Linear Actuator Aliveness	test that linear actuators power on/off. Power the linear potentiometers and verify that voltage output is what is expected from data sheet	1.2.2	DMM, Power Supply	Electronics Lab	Complete [Pass]
Load Cell Weight Sensor Accuracy	test load cell weight measurement accuracy with weights and compare to data sheet.	1.2.1	DMM, Power Supply, Weights	Electronics Lab	Complete [Pass]
Angle Sensor Accuracy	test inclinometer output accuracy on a known angle platform	2.5.1	DMM, Power Supply,Protractor	Electronics Lab	Complete [Pass]
Battery Aliveness	verify complete charge and discharge capabilities and compare to data sheet.	1.1.7, 2.3.1	DMM, Power Source	Electronics Lab	Complete [Pass]
PCB Aliveness	ICT (in circuit testing) check for shorts, resistance, capacitance, etc. with probe, dmm, and power supply	1.2.2	DMM, Power Supply, Probe	Electronics Lab	Complete [Pass]
SubSystem Level					
Mechanical					
Conveyor Belt Assembly	once the sprockets, motors, chains, scoops, and structural support has been assembled, test that everything rotates properly, chains dont slip, scoops fit.	1.2.2	None	Project Space	Complete [Pass]
Digging Force Test	Test the digging force of the scoops with a force sensor as they dig into the surface.	MO.1, 1.1.3, 1.1.6	Arduino, Force Sensor	Sandbox	Complete [Pass]
Electrical					
Motor Synchronization	test that both motors spin at the same rate and the encoders provide identical feedback data.	0.1	DMM, Power Supply	Electronics Lab	Incomplete
PCB & Electronics Compatibilty	test that all wiring/connections between Arduino, PCB, and electronics are compatible and the entire system has power when supplied power through power supply.	1.1.4,1.1.7	DMM, Power Supply	Electronics Lab	Incomplete
Linear Actuator Synchronization	test that both linear actuators actuate in unison and the potentiometers provide identical feedback data.	0.1	DMM, Power Supply	Electronics Lab	Complete [Pass]
Battery Compatiblilty and Power Distribution	Connect Battery to PCB & Electronics Compatibility test set up. Test that battery will provide power to all components rather than the power supply.	2.3.1, 1.1.7	DMM	Electronics Lab	Complete [Pass]
System Level					
Software Compatibility	test that sofware can recieve data from motors, linear actuators, load cell, battery and tilt sensor. Test that software user can send stop, start, sleep, safe mode commands to actuate motors and linear actuators.	1.1.1,1.1.2, 2.4.1,2.4.2, 2.4.3,2.4.4	Computer	Electronics Lab	Complete [Pass]
Software Autonomous Control Loop	test that once the start command is initiated, that the digger will autonomously start digging and the 'health data' is continously updated and displayed to the user.	0.3, 2.4.1	Computer	Electronics Lab	Incomplete
Processing Rate	test the rate of which the command is sent to the digger to when the digger begins performing the action. Test the rate that 'health data' is being updated to the user.	2.4.1,2.4.3	Computer	Electronics Lab	Complete [Pass]
Full-Functional Level					
Day In The Life	operate for a full 15 minutes or until the 0.5 kg simulated regolith collected. Verify that at least 0.5 kg of simulated regolith is gathered. All software modes will be performed and verified.	0.1, 1.1.4, 2.4.3	Computer	Sandbox	Complete [Pass]
Unoperable Tilt	place digger in an unoperable environment (plus/minus 5 deg) ensure the digger will respond correctly. The digger should notify the software user and enter sleep mode.	2.4.4, 2.5.1	Computer	Sandbox	Complete [Pass]
Unoperable Condition	place digger where it cannot dig into the ground (large rocks or tightly packed). Ensure that the digger can feed back motor encoder data quick enough to stop the motors and change the digging location to continue digging. If feedback data is not processed quick enough, the max motor current fuse will quit the power supply to the motor to stop the digger.	0.2	Computer	Sandbox	Complete [Pass]
Power Performance	operate digger for 15 minutes under modes that use maximum power consumption to ensure the battery will supply power to the digger the entire time.	2.3.1, 1.1.7	Computer	Sandbox	Complete [Pass]
Life Long Performance	Operate digger for 10 cycles of at least 15 minutes each cycle throughout the Spring semester. Ensure no components have material damage.	0.4, 2.1.2	Computer	Sandbox	Complete [Pass]

Figure 6: Test Overview

The table above lists every test the GOPHER performed. Tests progressed subsystem to full system level to ensure each component and subsystem functions correctly before final assembly. Tests are separated into Component, Subsystem, System, and Full Functional levels. Component level tests verify that each electronic or mechanical component is functional. Subsystem level tests verify that each subsystem works independently. System level tests verify that once each subsystem has integrated together that the entire system operates as expected. Full Functional testing verify GOPHER's top driving requirements and mission objective. Seen in the table above, all tests passed except for three tests. The three tests were discarded due to design changes of a switch to a single motor, no longer using a PCB, and having a non-autonomous system. The two most critical tests are highlighted in green, the Digging Force Test and Day in the Life Test. Both tests verify GOPHER's mission objective as well as many system requirements. Overall, with successful completion of testing, GOPHER is fully verified and ready for operational deployment.

2.2 Component Level Tests

2.2.1 Motor Aliveness and Max Current Test

The purpose of the Motor Aliveness test is to demonstrate the functionality of our motors to enable us to perform higher level sub system and system level tests. This includes integration of the motors into the digging arms, PCB integration, Arduino integration, and motor synchronization.
Procedure:

1. Turn on the power supply and oscilloscope.
2. Connect motor encoder leads to ground and the oscilloscope.
3. Set the power supply to 12 V.
4. Connect negative and positive leads of the motor to the ground and positive plugs on the power supply, respectively.
5. Verify that the motor is on and running.
6. Verify that the oscilloscope is receiving voltage values from the motor encoders.

The expected outcome of this test is out-of-the-box verification of the motors and the encoders. If the motors or the encoders are not verified to be in working condition immediately, it can cause significant delays later in the assembly process if the encoders are not outputting the correct data. This ensures a safe system with a reduced possibility of errors during integration. It is therefore crucial to determine if a motor is faulty as early as possible in the testing and integration phase to ensure we do not fall behind schedule.

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The purpose of the max current test is to demonstrate the functionality of our fuse that powers the motors off of a dedicated battery. This is an important safety verification that must be completed before any sub system or system level test that involves the motors. This is because if a motor binds or draws an unexpectedly high amount of current the chains could snap and be hazardous to the testing team. Thus, the fuse is an integral part of safety for the team, but also prevents any extra damage that would set the team back in testing.
Procedure:

1. Solder fuse to 12 V Battery with the XT-90 connector.
2. Set multi meter to measure ohms
3. Check the resistance of the fuse with digital multi meter by touching the ends to the two separate prongs of metal
4. Set the multi meter to continuity mode
5. Measure the continuity of the fuse to ensure connections

While the fuse was never blown during testing, we did notice issues with current draw across the whole system while attempting system-level and full functional-level tests. As the GOPHER unit was digging, employing a combination of extended depth change and angle change actuators, the rotations per minute of the motor were severely inhibited. We found the root cause to be the current required to sustain the linear actuators at their commanded distances, which reduced the amount of current available for the motor rotations per minute. Although no major changes were made to the design structure to accommodate this issue, the team was able to wire a second battery to the protoboard to separate the battery suite used by the motors from that used by the linear actuators. This modification allowed for a safer system by enabling us to isolate the increased motor current draw from the electronics bay in case it got stuck on a rock.

2.2.2 Load Cell Weight Sensor Accuracy

The purpose of the Load Cell Weight Sensor test is to demonstrate the accuracy of the load cell sensor in performing system-level tests. This included wiring the load cell to an Arduino with a Qwiic Scale

load cell amplifier. The first test conducted was to verify that the load cell was functioning properly by performing a load cell aliveness test.
Procedure:

1. Wire qwicc scale
2. Wire load cell
3. Clamp load cell onto the table
4. Put a Known weight hanging by a rope on the other end
5. See serial monitor data

It would be found out that the load cell would give back data in bits and not in pounds or kilograms. This led to a second test being operated to the load cell. An accuracy test was used the zero offset value and a calibration factor.

1. Wire Qwicc Scale
2. Wire Load Cell
3. Clamp Load Cell onto table
4. Write Zero Offset Bits of load cell
5. Add weight in intervals
6. Convert Bits to pounds

The expected outcome of this test is the verification that the load cell can accurately detect how much weight is being pushed into the load cell. On one of the load cells the zero factor was 219,000 bits and would increase 198,400 bits per pound. However, it was found out with multiple tests that the load cell's zero factor would change every test. This would make us implement a 5 second calibration test and zero out this offset using the GUI.

2.2.3 PCB Aliveness

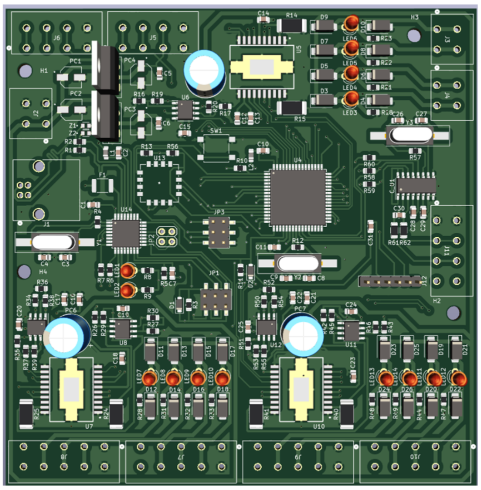

Figure 7: PCB

The primary objective of the PCB aliveness test is to verify both the design integrity and the assembly accuracy of the circuit board. This test entails connecting the PCB to a power supply and systematically testing all connections to ensure they are functioning as intended. Following this, the test includes bootloading the two main controller chips on the board: the ATmega1281 and the ATmegaU2. This procedure is critical for confirming that the components are operational and correctly interacting according to the design specifications.
Procedure:

1. Connect the PCB to the power supply.
2. Turn on the power supply, ensuring it provides at least 4 Amps.
3. Check for shorts on the board using a digital multimeter.
4. Use the digital multimeter to test all connections and verify voltage levels at different points on the power supply.
5. Connect the In-System Programmer (ISP) to the programming header on the board for the ATmega1281.
6. Load the bootloader onto the ATmega1281 chip.
7. Repeat steps 5 and 6 for the ATmegaU2 chip.

The primary objective of this test was to confirm that the PCB was functioning as expected and to identify any design flaws. The test results confirmed that there were no power shorts on the board, and power was correctly supplied to the necessary locations. However, a soldering issue that bridged connections on the ATmega1281 chip was identified. This issue was subsequently rectified, and the test was repeated. Despite these corrections, the bootloading of the microcontrollers failed. This was later discover to be a rest pull-up issue. However, due to time constraints the decision was made to switch to the electronics off ramp.

2.3 Sub System Level Tests

2.3.1 Digging Force Test

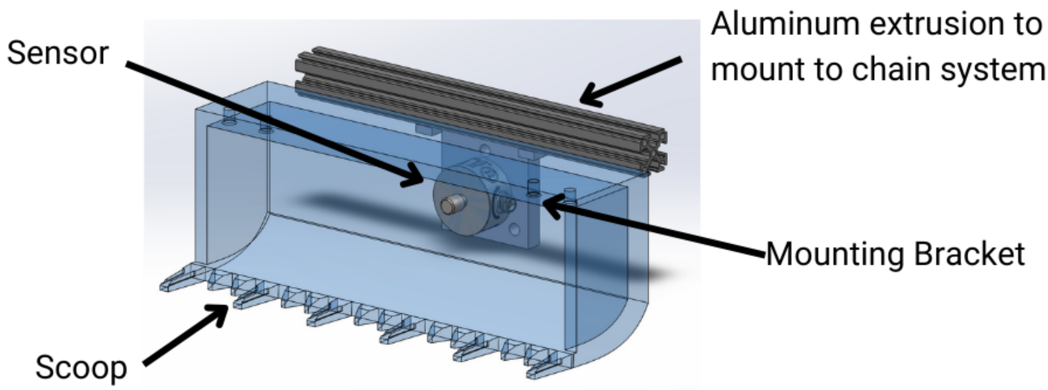

Figure 8: Bucket and Force Sensor for Test

The purpose of the Digging Force Test is to validate the Digging Force Model and Static Equilibrium Model by measuring the amount of force required to dig. To do this, the GOPHER was set up in the sandbox with a force sensor attached to a bucket which can be seen in Fig.(8)
Procedure:

1. Wire sensor and DAQ to the GOPHER and the computer.
2. Record the angle of scoop insertion with iPhone app.
3. Run MATLAB script.
4. Hand crank the system (using additional force as necessary) until the scoop passes through the sandbox ground, stopping just after a single dig.
5. Record data. Record digging depth.
6. Move system to different spot in the sandbox.

A hand was used as additional force in this case. It also served the purpose to keep the bucket at the measured angle. The setup of the force sensor (as shown in Fig. 8) meant that the force on the rear of the bucket would still be counted towards the total force. The test was done a total of 8 times. The Digging Force Model was calculated using different variations of the Fundamental Earth Moving Equation to give a prediction of how much force would be required for each bucket to dig in our sandbox. The expected results for the Mckyes Model (Earth) was 9.8 N, and the expected results for the Zeng Model (Moon) was 10.1 N. From the Static Equilibrium Model, the force required to tip the GOPHER was determined to be 102.5 N of force on Earth and 17 N on the Moon. The results from the Digging force test are shown below in Fig. **??**. The force profile for a test plotted against the Mckyes model is shown in Fig. 9

Trial	1	2	3	4	5	6	7	8
Max Vertical Force [N]	60	57	88	68	101	47	74	100

Table 1: Max Vertical Force Measurements

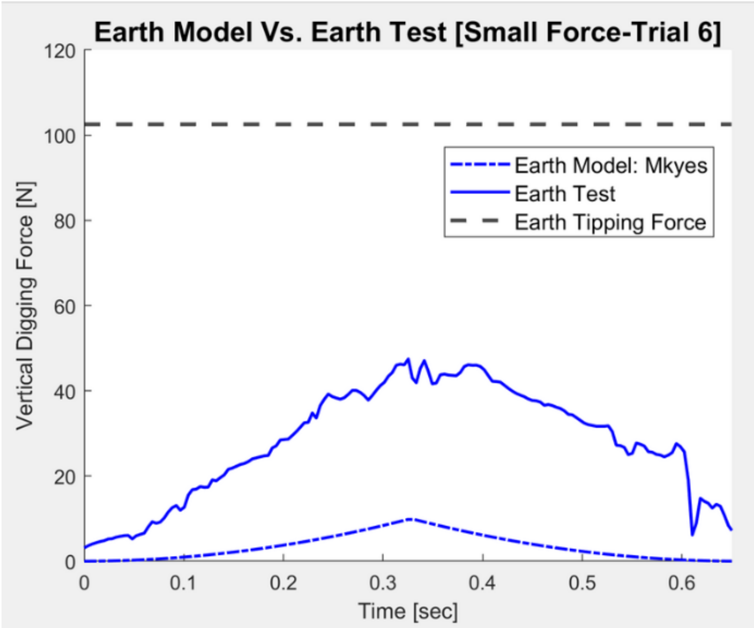

Figure 9: Profile of a Single Test Compared to the Mckyes Model

The actual force required to dig was significantly higher than the predicted force from either model, but still under the tipping threshold. The reasoning for the discrepancy with the models are due to a difference in materials; The models were designed to predict the force to dig in soil, which as high cohesion and adhesion properties, while rocks have a value of zero for each, causing the model to underestimate. The model also assumes the digging speed is constant, which was impossible due to the hand cranking. In addition, the test was performed shortly after a significant rainfall, causing the rock and sand mixture to be wet, greatly increasing the necessary force. The Zeng model was designed specifically for a moon environment (properties of regolith, 1/6 earths gravity, etc.) making it impossible to compare our test on Earth. The test was successful despite the discrepancies as the digging force never exceeded the tipping force.

If this test were to be performed again, it would be done under the power of the motors for a consistent digging velocity. Additionally, the bucket-sensor mount would have to be redesigned to be more stable on the excavator arm, negating the need for the stabilizing hand. Finally, the test would be performed when the sandbox was sufficently dry.

2.3.2 Conveyor Belt Assembly

The conveyor belt assembly testing was conducted in order to provide a strong foundation for higher level tests involving the entire digging arm. GOPHER uses a chain belt ladder system driven by a single motor within the digging arm. In order to create this system there are a total of eight sprockets. Two of which are used to take the motors output and transfer it to the larger chains which span the entirety of the digging arm. The remaining six sprockets are aligned along the center of the two sides of the digging arm. Using spacer along with a sprocket in the middle of the digging arm on each side the proper tension as well as alignment were achieved. This allows for the chain system to stay attached to the digging arm and the addition of a tension sprockets allows for support when the GOPHER is experiencing horizontal disturbances during the digging process. When the buckets are mounted to the chain system it also creates more stability and aids in keeping the chain system properly aligned. The test conducted on the fully assembled chain conveyor belt was to manually run the system via a hand crank in the sandbox. During this test it was clear the chain system was highly durable and functioned properly with the presence of sand and small rocks within the chain system. Throughout this test it was also clear the use of buckets and proper tension kept the two separate chain drives aligned even after multiple tests allowing for the buckets to optimally enter the sandbox surface.

2.3.3 Linear Actuator Synchronization

Validating the synchronization of both the angle change and depth change linear actuators for GOPHER was critical for a number of reasons:

1. Maintaining synchronization ensures that GOPHER's movements are predictable and controlled, reducing the risk of accidents or damage to the robot or its surroundings.
2. Synchronization helps optimize GOPHER's movements, ensuring that it operates smoothly and efficiently. This can lead to faster and more effective mining operations.
3. Precise control over GOPHER's movements is essential for accessing and extracting regolith. Synchronization ensures that the buckets are positioned accurately.
4. If the angle and depth changes are not synchronized, it could lead to GOPHER getting stuck or causing damage to its components or the mining environment.
5. Proper synchronization can help reduce wear and tear on GOPHER's components, leading to lower maintenance costs and longer operational life.

The linear actuator synchronization test consisted of the following:

1. **Hardware:** Connect the linear actuators to the PWM outputs of an Arduino micro-controller. Ensure that the actuators are connected in a way that allows them to be controlled independently but can be synchronized when required.
2. **Control Software:** Develop software that allows for control the PWM signals sent to each linear actuator. The software contained functions to independently control the position (angle or depth) of each actuator and to synchronize them when necessary.
3. **Test Cases:** Stress test to determine the maximum allowable margin for the difference in stroke length between a set of linear actuators. Electrical test to ensure that a maximum PWM command corresponds to the same extension length and speed for each linear actuator.

From the linear actuator synchronization tests, we determined that the maximum allowable difference in stroke length was 2% before our factor of safety for our mounting bracket factor of safety was exceeded, though the PLA material they were made from could tolerate a difference of 10% before structural failure. We also determined that an independent 12V battery was required to ensure that the motors would not interfere with the current requirements of four running linear actuators.

2.4 System Level Tests

2.4.1 Software Compatibility

There are two primary components that are designed to ensure seamless interaction across the GOPHER's software architecture: the Python-based control GUI on an external laptop and the Arduino microcontroller housed within the robot.

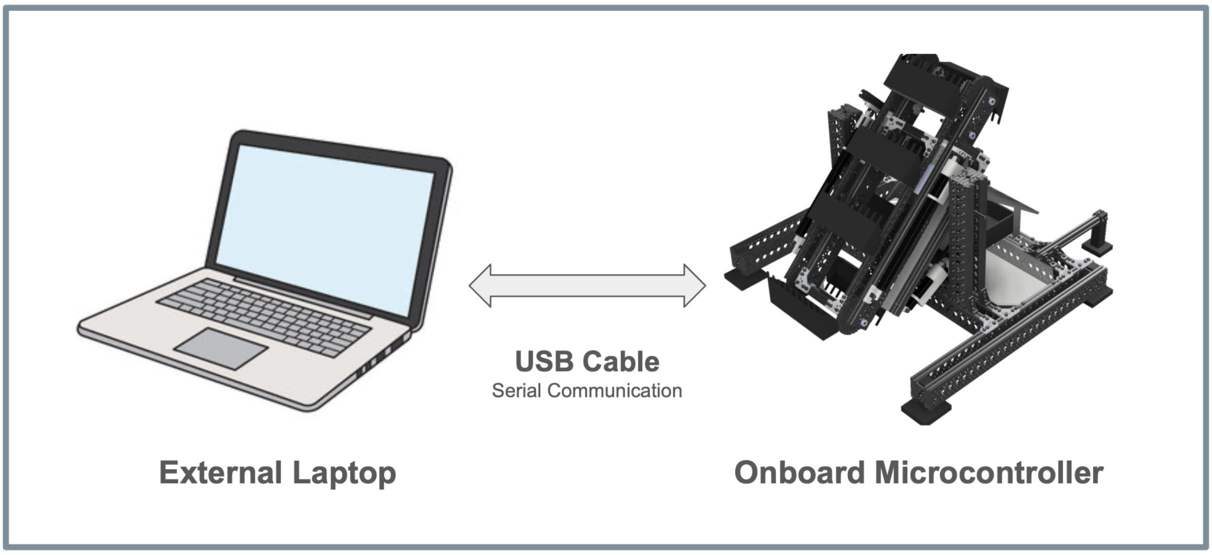

Figure 10: Software Component Diagram

Determining and maximizing the reliability between these elements is integral to ensuring precise control, real-time health monitoring, and effective data acquisition during a harvesting cycle.

Python-Based Control GUI

An external laptop is used to host the GOPHER control panel, which was designed with Qt Designer software and converted to a Python script using PyQt5. During operation, the laptop runs this Python script that graphically displays and functionally supports the control commands and live data feeds. Each user action, such as a button click, numerical input, or opening/closing of the window is programmed to send an appropriate response to the robot's microcontroller. This interface is instrumental in displaying the robot's real-time status, facilitating the sending of commands, and storing the collected sensor data.

To verify the reliability and functionality of the design, we implemented a testing protocol to verify the data being sent to and from the microcontroller. Initially, this testing involved using a standalone Arduino Uno as a simplified model of the robot's control system. It was programmed to activate its LED in specific patterns depending on which button was pressed on the control GUI. Then, after implementing manual control, the Uno was programmed to reproduce its actuator length or motor speed inputs back to the laptop from which we could verify the success of it by printing to the PowerShell terminal. Finally, to verify the live-data feed abilities, the Uno was programmed to randomly generate numbers to send to the laptop, and the graphs successfully displayed the simulation data at the correct specified rate. This two-way communication test ensured that not only could the laptop send commands effectively, but it could also process incoming data from the Arduino, mimicking the data flows expected during actual mining operations. These tests were also pivotal in solidifying confidence in the control GUI's reliability.

Arduino Microcontroller

The Arduino microcontroller housed onboard GOPHER is tasked with a critical role as well in managing direct hardware interactions and executing real-time operational commands. This microcontroller is coded in C++ using the Arduino IDE, and is programmed to interface with several key components: the load cell force sensor, the inclinometer, actuators, and motors. Each of these components plays a vital role in the software's functionality. The load cell measures the weight of the hopper's collected material during mining, providing feedback that is used for ensuring a successful collection. The inclinometer, communicating via I2C, measures the robot's tilt angle and allows us to ensure stability during operation. Both the motors and actuators operate under Pulse Width Modulation (PWM) control, which allows for precise adjustments to their speed and position.

With each of these separate components having different handling operations and communication protocols, many separate comprehensive tests were conducted to ensure the functionality of each one with the Arduino. First, each component was connected to the microcontroller with its own standalone Aruduino sketch tailored for that specific component. Then, for the actuators and motors, we visually verified their operation with our inputs to confirm that the PWM signals correctly controlled their movements. For the Load Cell and inclinometer testing, we physically manipulated the sensors while looking at the sketch's serial monitor to read the outputs from the sensors. This process verified that the sensors were responsive and accurate in their data reporting. Following this testing, we could then integrate each component into a single system within the Arduino environment with confidence in the software's functionality and the data reliability. So, after full integration, the day in the life tests verified the functionality on the software system in full operation.

2.4.2 Inoperable Tilt Test

The inoperable tilt test was designed to fulfill requirements 2.4.1 (the digger shall be capable of communicating health updates to the ground station), 2.4.4 (the digger shall be able to report the moon ground conditions), and 2.5.1 (the digger shall be able to measure the moon ground conditions). These in turn support requirement 1.1.1 (the digger shall have compatible data communications with the mother rover and the ground station). The test itself was designed to show that GOPHER can sense and communicate its inclination to the operator, including if that inclination is nearing the cut-off angle determined by the tipping force models.

This test required the testing sandbox of simulated regolith and sand; a calibrated inclinometer to measure GOPHER's tilt, as well as a level to confirm accurate measurements; the ground station and operator to control the digger; and the GOPHER itself far enough along in its production to at least be able to push against the ground and process and communicate the inclinometer data. The test was set up with GOPHER sitting in the simulated environment, connected to a team member's laptop running the control GUI. GOPHER was then turned on so that the inclinometer data could start being collected and sent to the laptop, or ground station. A level was used in the form of a phone app to confirm the tilt shown on the GUI was correct (Req. 2.4.4, and 2.5.1). Once these things were verified, GOPHER was started and made to push against the ground, showing that the inclination shown on the GUI changed with tilt (Req. 2.4.1), as well as again confirming with the phone app that the inclination read by the GUI was reasonable. The final part of the test involved a team member manually tilting GOPHER while it was stopped but sending data to show that the GUI will display when GOPHER tilts too far (Req. 2.4.1). See [FIG].

The measurements taken during this test were from the inclinometer, as well as the phone level that ensured the inclinometer was correct. The inclinometer data was collected and sent to the GUI once every second, at a resolution of [NUMBER HERE]. This test worked well, albeit with some delay between the tilt of GOPHER and the measurement of that tilt. At the speed GOPHER would potentially be tilting while in operation, the delay would not be significant enough to disrupt the mission. Considering this, the test showed GOPHER is able to meet the requirements that it be able to communicate health updates to the ground station, as well as measure and report moon ground conditions. These fulfilled requirements show that Req. 1.1.1 is met, having compatible data communications with the ground station, with there being no mother rover with which to have communication.

Sources of uncertainty in these measurements are mainly due to calibration of the inclinometer, as well as its resolution. Due to the nature of the environment and digger motion, though, this uncertainty is not significant enough to greatly affect the test results. Sources of uncertainty in the test as a whole, however, lie mainly in human error and necessary involvement. Repetition of data is unrealistic due to the inconsistent nature of both the test environment and the angle at which the team member tilted GOPHER. Since neither of these could be consistent each test, verification of receiving data was carried out by visually confirming it was appearing on the GUI, and verification of reading inoperable tilt conditions was likewise carried out by watching the GUI readout to see when the limit was reached. These sources of uncertainty do not significantly affect the verification of the relevant requirements, in terms of requirements 2.4.1 and 2.4.4, all that was needed was to visually confirm communication between GOPHER and the ground station. Requirement 2.5.1 is the one most affected by the uncertainty in measurement, however the uncertainties present in our test set-up are not enough to prevent this requirement from being met.

2.5 Full-Functional Level Tests

2.5.1 Day in the Life Test

The purpose of the Day in the Life test is to prove that GOPHER can meet all mission and functional requirements. This test takes place in the simulated mission environment, referred to as the sandbox. This test will prove that GOPHER can successfully collected the required 0.5kg of regolith within the

15 minute time frame allotted without physical intervention by on-site personnel. The simulated day of operation begins with GOPHER's placement in the sandbox, simulating the mother rover dropping GOPHER off at a chosen digging location. Once GOPHER has been placed, it is powered on and connected to a team member's laptop, simulating a ground operator. Once GOPHER is successfully connected to the laptop and is ready to dig, large, unwanted rocks are manually mixed into the digging area. This is to test GOPHER's filter on top of the hopper to verify that it prevents large, unwanted chunks of regolith from being collected. Once mixing is complete, the controlling team member initiates the motors and actuators. Over the course of the digging cycle, the controlling team member continually adjusts the actuators and motor speed to in order to collect regolith. Between the load sensor on the GOPHER and visual estimations, when .5kg of regolith had been judged to have been collected, the GOPHER was then stopped and placed in sleep mode. All motor functions cease and all actuators return to resting position.

Day in the Life testing day included three trials, the first two of which were simplified day in the life tests, which did not include the filter or larger unwanted rocks in the digging area. The batteries had enough power that all three tests were concluded without needed a break for recharging. In terms of system resilience, the PLA 3D printed buckets performed beyond any expectations of the team. Over the course of various tests, not just the day in the life, the buckets were subjected to at least of 150 minutes of operation, and not a single tiger tooth was broken on any bucket. Abrasion on the teeth was evident, but was also much lighter than expected. Overall, the PLA buckets suffered virtually none of the attrition the team expected of them. Despite getting temporarily stuck during operation multiple times, GOPHER still managed to complete all requirements without any motor or actuator damage. The sealing methods employed on the top plate shielding the electronics prevented sand or dust from entering the electronics housing. The chain drive did not jam, despite the presence of wet sand on them. In two instances, a rock became jammed in between the extended depth change actuator rods and the frame. One case, the rock was removed by GOPHER during actuator retraction. In the other case, it stayed in place even after actuator retraction but did not affect operations nor cause damage.

Trial	**Description**	**Time**	**Regolith Collected**
1	Simplified Day in the Life: No larger interspersed rocks. Run for full time period for maximum accumulation.	15:00 Minutes	0.97 kg
2	Simplified Day in the Life: No larger interspersed rock. Run until 0.5 kg of regolith is collected.	5:00 Minutes	0.52 kg
3	Full Day in the Life: Larger interspersed rocks. Run until 0.5 kg of regolith is collected.	11:42 Minutes	0.56 kg

Table 2: Trial Descriptions and Results

As seen in 2, all three trials, including the full-fledged Day in the Life with larger rocks mixed, GOPHER completed all mission requirements. Despite the presence of unwanted larger rocks, we were able to collecteD all required regolith. However, the presence of larger rocks did increase the amount of time to hit the target amount. In Trial 2, GOPHER collected the target 0.5kg in five minutes. With larger rocks, that time was more than doubled, taking 11:42 to hit the target amount.

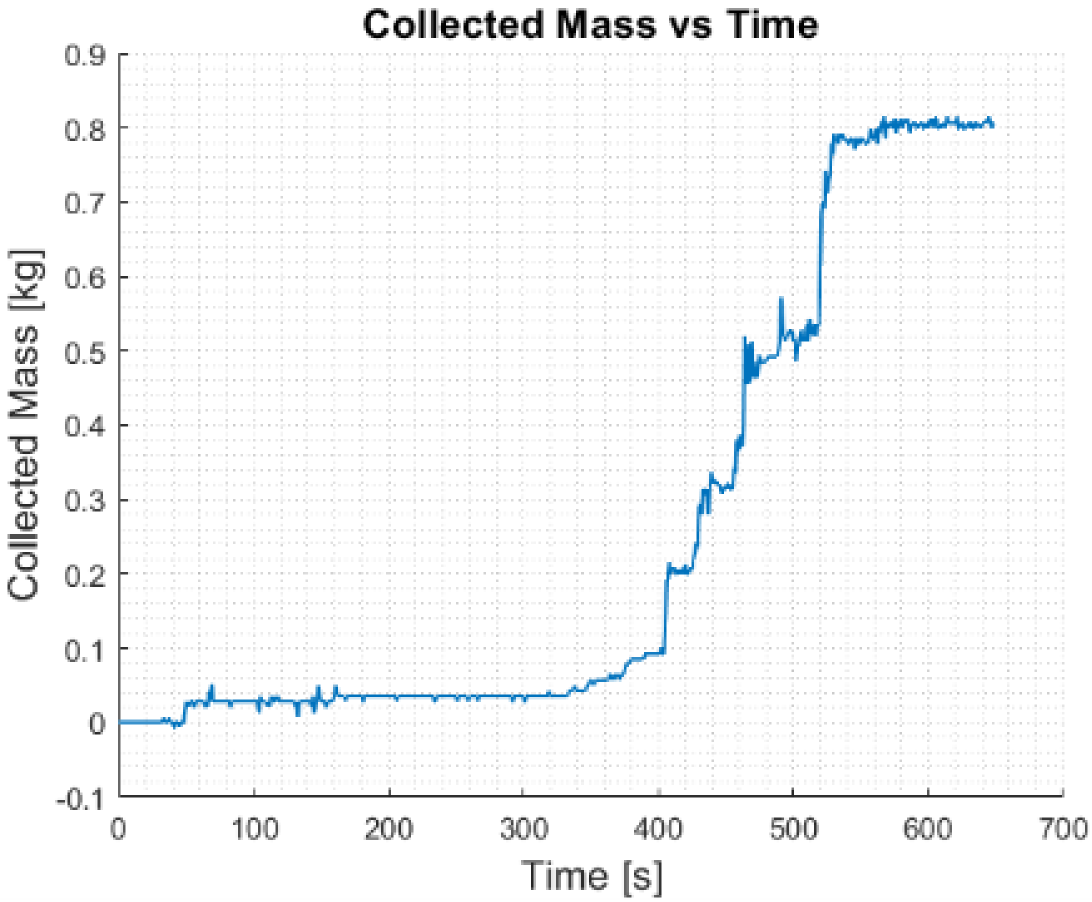

Figure 11: Trial 3 Mass vs Time

As seen in 11, Trial 3 regolith collection was extremely inconsistent, with nearly no collection for the first 400 seconds of the digging cycle. Most of the regolith collected was collected in just four scoops. A key assumption of our mass collection model was a consistent dig rate. As seen here, that was not the case.

2.5.2 Power Performance

The power performance section of testing in the full functional level is vital to determining the overall efficiency of our design and it's applicability outside of a testing environment.

During the component level tests while testing individual electronic components we used a separate power supply to monitor the performance of each system. This testing allowed us to understand the functionality of our system from a more robust perspective. For example, it allowed us to gauge the current draw of the linear actuators, and the motors separately but also while running together. While performing a sub system level test of running our actuators together on the manipulation of the conveyor belt we found that one of our original depth change actuators drew a higher amount of current and extended significantly slower than the others; this led to the team decision to replace the linear actuator. Near the final stages of testing in the day of the life, we noticed current draw issues between the motors and the linear actuators; which led us to investigate incorporating a second battery suite for the motors to allow for full functionality on all electronic components. The team decided to incorporate a secondary battery, and was able to successfully solve the current draw issue completing the day in the life test.

2.6 Lifelong Performance Test

The critical Full-Functional Level test of the Life Long performance was a test to see the ability of the GOPHER to operate for ten cycles totalling 150 minutes. Throughout this test there was no maintenance or physical intervention required except to clear simulated regolith from the hopper after every 15 minute interval. Multiple times throughout the entire test small rocks would lodge themselves between the support structure of the digging arm and the linear actuators. With the ability to manually control the system a change in depth or angle via the linear actuators was always enough to free any rocks that could pose problematic for continued digging. The buckets mounted on the digging arm experienced minimal wear throughout the test and never needed to be changed. The same is true for the filter mounted above the hopper used for deflecting the large rocks interspersed within the sandbox. The main factor in the successful completion of this test was the use of the chain belt ladder system previously outlined within this section. During this life long performance test sand and small pieces of gravel found its way into all parts of the digging arm, it was clear to see and hear the presence of sand within the linear actuators and the chain system. Due to the strength of the linear actuators and the tension in the chain system any sand was either crushed or pushed away from the linear actuators, this led to the full system functioning efficiently throughout the entire test with no components locking up. This design is extremely durable and needed no maintenance after the test was complete except for the recharging of batteries. The use of a dual battery system allowed us to be able to operate the entire 150 minutes without needing to recharge the batteries. This test verified the mission success requirement 0.4: The digger shall be capable to operate for at least 10 cycles. This also satisfied the child requirement 1.1.10.

3 Lessons Learned and Future Work

3.1 Key Lessons Learned

Introduction

The lessons learned from our senior project not only reflect the challenges and achievements encountered but also serve as valuable insights for future projects. This section discusses the impact of these lessons on our project's execution and outcome, emphasizing both our successes and the areas where improvements are necessary.

Team Management

1. **Setting Clear Responsibilities and Deadlines**
   The project's initial success was largely due to well-defined roles and strict adherence to deadlines, particularly during the first semester's focus on the GOPHER excavator's design and modeling. Clear responsibilities allowed for a smooth and efficient workflow, maximizing productivity and minimizing confusion. However, as the project moved into the second semester, sticking to these deadlines proved challenging. The increasing complexity of the project led to delays, highlighting the need for more adaptive deadline management to accommodate unforeseen complications.

2. **Workload Management**
   Establishing an environment where team members felt comfortable seeking help when overwhelmed was crucial. This openness prevented bottlenecks and ensured that issues were addressed promptly, maintaining morale and project momentum. This approach should be a standard practice in future projects to foster a supportive and efficient team dynamic.

Research and Design

1. **Leveraging Existing Knowledge**
   Our research phase was significantly enhanced by drawing on existing studies and projects, particularly from fields like terrestrial gravel mining. This approach not only informed our design process but also saved us from repeating mistakes made by other teams, such as those related to custom chain linkages.

2. **Predictive Troubleshooting**
   While we benefitted from existing knowledge, our project also revealed gaps in our initial research, particularly in predicting practical assembly challenges. Future projects should include a phase dedicated to predictive troubleshooting, especially for complex assemblies anticipated in the design.

Assembly and Integration

1. **Real-world Application vs. CAD Models**
   The transition from CAD models to physical assembly highlighted significant discrepancies that affected our assembly timeline and budget. Future projects should factor in additional time and resources for the assembly phase, anticipating challenges that are not apparent in digital models.

2. **Creative Problem Solving in Testing**
   The necessity for creative solutions, such as reconfiguring parts for manual tests when motors were unavailable, was a critical learning point. This flexibility should be embedded in the planning of future tests, allowing for alternative solutions when standard procedures falter.

Conclusion

The lessons learned from this project have not only shaped our understanding of project execution but also prepared us for future challenges in engineering and design. By adopting flexible planning, fostering a supportive team environment, and integrating thorough and anticipative research practices, future projects can achieve greater success and innovation.

3.2 Future Suggestions

Introduction

The insights and experiences gained from our project not only highlight areas of success but also offer a roadmap for future improvements. This section outlines practical suggestions aimed at enhancing project outcomes in similar future endeavors.

Technical Development and Enhancements

1. **Advanced Simulation Techniques**
   To better anticipate real-world challenges, future projects should incorporate more advanced simulation techniques early in the design phase. This would help in identifying potential issues in assembly and integration that are not evident in CAD models.

2. **Modular Design Principles**
   Implementing modular design principles could simplify both assembly and troubleshooting. By designing components that can be easily interchanged, future projects can reduce downtime during testing and maintenance phases.

Project Management Improvements

1. **Dynamic Scheduling**
   Incorporating a more flexible and dynamic approach to scheduling could mitigate the impact of

unforeseen delays and challenges. This involves regular schedule reviews and adjustments, ensuring that the project adapts to ongoing changes and discoveries.

2. **Enhanced Resource Allocation**
   Better anticipation of resource needs for critical phases such as testing and assembly is crucial. Allocating additional resources, both human and material, can prevent bottlenecks and ensure that the project stays on track.

Team and Communication Strategies

1. **Continuous Skill Development**
   Encouraging continuous learning and development within the team can enhance project outcomes. Scheduled training sessions on the latest technologies and methodologies can keep the team updated and ready to tackle complex challenges.

2. **Iterative Feedback Mechanisms**
   Implementing iterative feedback mechanisms can improve communication and efficiency. Regularly scheduled reviews where team members can discuss challenges and progress will foster a more collaborative environment and enhance project deliverables.

Long-term Strategic Initiatives

1. **Integration of Autonomous Systems**
   For projects like the GOPHER, integrating autonomous control systems could significantly enhance operational efficiency and accuracy. Future projects should explore the inclusion of AI-driven solutions to automate routine tasks and processes.

2. **Sustainability Considerations**
   Incorporating sustainability into the project's lifecycle—from material selection to end-of-life disposal—can not only reduce environmental impact but also align with global sustainability goals. Future projects should prioritize eco-friendly materials and processes.

Conclusion

The suggestions provided aim to build upon the strengths and lessons learned from this project, guiding future efforts towards more successful and sustainable outcomes. By embracing these recommendations, future projects can not only meet but exceed the benchmarks set by this endeavor.

3.3 Additional Work

Introduction

Building on the foundation laid by our project, additional work is proposed to refine and expand the capabilities of the GOPHER excavator. This section outlines crucial areas where further engineering analysis, design changes, and testing could significantly improve performance and meet project requirements more effectively.

Engineering Analysis and Models

1. **Battery Charge Level Modeling**
   Developing a predictive model for the battery charge level throughout each cycle could provide critical insights into energy management and operational efficiency. This model, combined with real-time data acquisition, would allow future teams to optimize the digger's energy usage and ensure it meets endurance requirements during extended operations.

2. **Structural Analysis of Assembly Components**
   Conducting a detailed structural analysis of assembly components could identify potential weaknesses not apparent during the initial design phase. This analysis would help in redesigning components to withstand operational stresses and improve overall durability.

Design Changes

1. **Modular Component Design**
   Redesigning certain components to be modular would facilitate easier assembly, maintenance, and potential upgrades. This approach would not only simplify the physical integration but also allow for quicker adaptations to the digger based on testing feedback and changing operational requirements.

2. **Enhancement of Autonomous Capabilities**
   Integrating more robust autonomous control systems would enable the GOPHER to perform more complex tasks independently. This change is crucial for operations where manual control is impractical or impossible, such as extraterrestrial or remote terrestrial environments.

Further Testing

1. **Extended Life Long Performance Tests**
   Conducting more extensive and rigorous Life Long Performance Tests would validate the endurance and reliability of the GOPHER over longer operational periods. These tests should include scenarios under varied environmental conditions to simulate real-world challenges.

2. **Autonomous System Deployment Tests**
   Testing the integration and functionality of autonomous systems in controlled and uncontrolled environments would provide valuable data on the system's reliability and operational limits. This testing is essential to ensure that the digger can perform its intended tasks autonomously as designed.

Conclusion

The additional work outlined above is critical for advancing the GOPHER project beyond its current capabilities. By focusing on these areas, future teams can address the existing limitations and enhance the system's reliability and functionality, ensuring that it meets all intended project requirements and can adapt to new challenges.

4 Individual Report Contributions

Name	Spring Contribution	Report Contribution	Signature
Flynn	CAD Models, PCB Design, Con Ops, FBD, GAANT Chart	Preamble, ConOps, Critical Elements, Hardware Breakdown, PCB Aliveness Test, Editing	*Flynn Hill*
Hayden	Risk, PCB Design, Sensor Analysis, Actuator Code, Systems Integration	Driving Requirements, Linear Actuator Sync Test, FBD	*Hayden Gebhardt*
Ginger	Testing Lead, Digging Force Test, Digging Models, Test Documentation	Testing Introduction, Report Editing	*Ginger Olson*
Alex	GOPHER Assembly, Scoop Testing, Digging System Test	Day in the Life Test Description, related figures	*Alexander Havens*
Isaac	Assembly of the electronics sub system, Testing and programing of the Load Cell and Accelerometer	Load Cell Weight Sensor Accuracy Test,	*Isaac Chavarria*
Joshua	Scoop Test, FBD Verification, Physical Design / CAD, PCB Assembly, Motor and Linear Actuator Testing, Soldering	Motor Aliveness and Max Current, Power Performance	*Joshua Camp*
Zachary	CFO duties, GOPHER Assembly, Testing Assistance	Digging Force Test Breakdown	*Zachary Faith*
Ben	Digging System Assembly, GOPHER Assembly	Conveyor Belt Assembly Test	*Benjamin Klementovich*
Orion	Actuator Synchronization Code, Arduino Code	Inoperable Tilt Test	*Orion Rozance*
Jack	GUI Implementation, Arduino Driver, Full Software subsystem Integration	Software Compatibility Test	*Jack Erstad*

5 Individual Project Goals and Self-Assessment

Student Name	Team Role(s)	Goals (100 words or less)
Flynn Hill	Project Manager	**Original Goals:** As project manager, my goal was to lead our team of 10 in successfully completing our college senior project, ensuring effective communication, meeting deadlines, and maintaining high standards despite anticipated challenges. **Self Assessment:**Despite facing several challenges, including coordinating a large team and dealing with unforeseen issues, I managed to keep the project on track. Our team worked well together, and we were able to complete the project successfully, learning a lot about collaboration and problem-solving along the way.
Alex Havens	Mechanical Subteam Lead	**Original Goals:** As the Mechanical Subteam Lead, my goal was to spearhead design and assembly of the frame and excavator arm, ensure deadlines and mission requirements were met while maintaining effective communication within the team and within the project group as a whole. **Self Assessment:** Despite facing challenges in both design work and in assembly, our project was a success. I was able to lead the mechanical team to successfully design and assemble GOPHER, which met all requirements.
Zachary Faith	CFO, Mechanical	**Original Goals:** To learn how to operate as a team of engineers and learn how to complete deliverables for a client, in addition to keeping our team under budget **Self Assessment:** I definitely learned a lot this semester. I would say I was able to accomplish these goals, because I was able to write the reports required, I operated well with the team, and we still have a little over $400 left of our original budget. I also helped with the testing for the digging force test, and of course helped assemble the GOPHER.

Student Name	Team Role(s)	Goals (100 words or less)
Isaac Chavarria	Electrical Sub-team Lead	**Original Goals:** My goal is to oversee the testing and integration of the custom PCB board. This will include soldering and testing the PCB aliveness. Also being able to wire, and inspect electronics components, to make sure the G.O.P.H.E.R operates smoothly. The goal will be considered successful is the G.O.P.H.E.R meets 2.5.1, 2.3.1 and 0.3. **Self Assessment:** In my role, I had to think quickly on my feet when electronic components failed, and fortunately, my solutions were effective. I took the initiative to learn new skills as needed, and I was consistently available to support my team. However, My contributions included wiring and coding the Arduino.
Ginger	Test Lead, Mechanical Sub-team	**Original Goals:** For this semester, my goals include creating and leading test processes, creating testing plans, procedures, and documentation, analyzing dat, and developing models to cover all requirements. Assisting in mechanical assembly, and collaborating with the mechanical sub team was also part of my goals. **Self Assessment:** I believe I satisfied my goal completely. I successfully created test documentation, plans, and performed all major tests, provided major contributions to TRR, 3d printed/iterated designs, and assembled the GOPHER with the mechanical team.
Ben Klementovich	Mechanical Sub-team	**Original Goals:** My goal is to continue developing and assembling the regolith digging system on the G.O.P.H.E.R. More specifically I will fabricate, prototype, and test the buckets for the bucket ladder digging system. This goal will be considered successful if tests show the G.O.P.H.E.R. meets mission success criteria 0.1, 0.2, 0.3, and 0.4. **Self Assessment:** I assisted in assembling the mechanical structure of the regolith digging system with Alex Havens, achieving my first goal. My contributions extended to the G.O.P.H.E.R.'s support structure, installing struts, mounts for linear actuators, and bases for electrical components. I participated in the testing of the buckets with the team. We successfully met success criteria 0.1 to 0.4.

Student Name	Team Role(s)	Goals (100 words or less)
Hayden		**Original Goals:** My main goal was to successfuly lead the fabrication and integration of the various subsystems on the GOPHER ensuring it meet all requirments. Addtionaly my goal this semester was to assist the software subteam in developing the main engine and GUI **Self Assessment:** The GOPHER successfully meet all requirements underlining a successful project. Although, off ramps had to be taken to complete the design within the time frame.
Jack	Software Sub-team	**Original Goals:** My goal was to create an effective and reliable software system facilitating the flow of data throughout the robot. Developing and testing a GUI while simultaneously testing it while implementing the embedded software would allow us to ensure the reliability of each individual data flow and its communication throughout the robot and to the GUI. **Self Assessment:** The GUI was successfully developed, and the plan of testing on each electronics at a time allowed a slow and streamlined debugging process, so toward the full assembly and testing of the robot we were confident in the reliability of all software components. We also were able to complete all of the required tests and subsequent verification of all of the driving requirements.
Josh		**Original Goals:** My main goal was to take electronic workshops to help the design, fabrication, and testing of the PCB, electronics equipment, and the full GOPHER system. **Self Assessment:** I believe that I fully completed my goals for the system that I originally set out to complete. I successfully took all of the electronics workshops through the Surface Mounted Technology 2 workshop. This allowed me to be one of the main members active in assembly and testing of the PCB aand teesting of the load cell and the linear actuators. When we switched to the off-ramp I was able to support the team in assembling protoboards and the various electrical equipoments necessary to integrate the electronics into the Arduino.

Student Name	Team Role(s)	Goals (100 words or less)
Orion		**Original Goals:** My original goal this semester was to lead the Software subteam and deliver a complete software sub system that would fufull the driving rquirments. **Self Assessment:** The software subsystem was effectivly delived with the help of Jack on the electronics sub team and Hayden. Ovearll, I would say that I completed all of the required goals that were set for the electronics sub team. In the future better communicating with the other sub team leads could help accelerate testing and prevent bottleneck.

6 Appendix

6.1 Requirement Flow-Down

Level 0: Functional				
Requirement Number	Requirement	Parent Requirement	Child Requirement	Verification Method
MO	**Mission Objectives**			
MO.1	Design a small, stationary lunar digger to mine regolith from the surface of an off-world environment [e.g. Moon]		1.1.4, 1.1.7, 1.1.8, 1.1.9, 2.2.1	
0	**Mission Success Criteria**			
0.1	The digger shall be able to extract regolith of any size up to 2x2x2 cm in volume		1.2.2, 2.1.2	
0.2	The digger shall be able to harvest regolith when larger rocks (5-8cm in diameter) may be randomly interspersed		1.2.3, 2.1.1	
0.3	The digger shall be capable of digging continuously to extract 0.5 kg of regolith in 15 minutes or less		1.2.1	
0.4	The digger shall be capable to operate for at least 10 cycles		1.1.1, 1.1.2, 1.1.5, 1.1.6, 1.1.10	
	A cycle is defined as the robot digging for up to 15 minutes with independent power			
C	**Constraints**			
C.1	The digger shall be able to be contained and transported in a payload volume of 61x61x61 cm		1.1.3	I
C.2	The digger shall have a maximum weight of 23kg			I
C.3	The digger shall not exceed cost of $4000			I
Level 1: System Requirements				
Requirement Number	Requirement	Parent Requirement	Child Requirement	Verification Method
1.1	**Mission Design**			
1.1.1	The digger shall have compatible data communications with the mother rover and the ground station	0.4	2.4.1, 2.4.2, 2.4.3, 2.5.1	D
1.1.2	The digger shall be able to communicate with the ground station (wired).	0.1	2.4.3	I
1.1.3	The digger shall maintain a stationary position on the surface of the environment	MO.1	2.1.4	A
1.1.4	The digger shall accept start, stop, and sleep commands from the ground station	0.1	2.5.2	I
1.1.6	The digger shall operate in a low gravity environment $\sim$1/6 of Earth's gravitational pull	MO.1		I
1.1.7	The digger shall provide its own power for the mission	0.4	2.3.1	T
1.2	**Lunar Digger System**			
1.2.1	The digger shall harvest a total of 0.5 kg of regolith material per 15-minute dig cycle	0.3		D
1.2.2	The digger shall operate and perform digging operations to harvest regolith(simulated as gravel) that is buried below a 2 cm layer of sand	0.1		D
1.2.3	The digger shall be able to harvest regolith when larger rocks (5 to 8 cm in diameter) maybe randomly interspersed	0.2		D
Level 2: Sub System Requirements				
Req. Num.	Requirement	Parent Requirement	Child Requirement	Verification Method
2.1	**Mechanical**			
2.1.1	The digger shall be designed to dig through a 2 cm layer of sand	0.1		T, D
2.1.2	The digger components shall be designed with a lifespan of 150 minutes	0.4		A
2.2	**Power**			
2.3.1	The digger shall sustain power for no less than 15 minutes and no fewer than 10 cycles	1.1.7		T
2.3	**Software**			
2.4.1	The digger shall be capable of communicating health updates to the ground station	1.1.1		I
2.4.2	The digger shall communicate with the ground station (wired or wireless).	1.1.2		I
2.4.3	The digger shall be responsive to user commands at any point in the digging cycle	1.1.1		I
2.4.4	The digger shall be able to report the moon ground conditions (will operate within TBD grade)	1.1.1		
2.4	**Electronics**			
2.5.1	The digger shall be able to measure the moon ground conditions (will operate within TBD grade)	1.1.1		I

Table 3: GOPHER Requirements Flow-down

6.2 Risk Assessment Matrices

Risk Consequence Categories

Risk	1 – Very Low	2 – Low	3 – Moderate	4 – High	5 – Very High
Safety	Negligible, no impact	Could cause the need for minor first aid treatment	May cause minor injury or occupational illness or minor property damage	May cause severe injury or occupational illness or minor property damage	May cause loss of life or permanent disability or destruction of property
Technical	No impact to full mission success criteria	Minor impact to full mission success criteria	Moderate impact to full mission success. Minimum mission success criteria is achievable without margin	Major impact to full mission success criteria. Minimum mission success criteria is achievable with margin	Minimum mission success criteria is not achievable
Schedule	Negligible, no schedule impact	Minor impact to schedule milestones but within margin, no impact to critical path	Impact to schedule milestones, requires accommodation within margins, moderate impact to critical path	Major impact to schedule milestones, major impact to critical path	Cannot meet schedule and program milestones
Cost	**<2%** increase over allocated, negligible impact on reserves	Between **2% - 5%** increase over allocated and manageable within reserves	Between **5% and 7%** increase over allocated and unmanageable within reserves	Between **7% - 10%** increase over allocated, and/or exceeds proper reserves	**>10%** increase over allocated, and/or can't handle with full reserves

Figure 12: Risk Consequence Categories. Adapted from NASA standards.

Likelihood Estimates

Likelihood	1 – Very Low	2 – Low	3 – Moderate	4 – High	5 – Very High
Safety (est. probability of safety event occurring)	0 < PS <= 10e-5	10e-5 < PS <= 10e-3	10e-3 < PS <= 10e-2	10e-2 < PS <= 10e-1	PS > 10e-1
Technical (est. probability of technical event occurring)	0% < PT <= 2%	2% < PT <= 15%	15% < PT <= 25%	25% < PT <= 50%	PT > 50%
Schedule (est. probability of schedule event occurring)	0% < PSC <= 10%	10% < PSC <= 25%	25% < PSC <= 50%	50% < PSC <= 75%	PSC > 75%
Cost (est. probability of cost event occurring)	0% < PCO <= 10%	10% < PCO <= 25%	25% < PCO <= 50%	50% < PCO <= 75%	PCO > 75%

Figure 13: Risk Likelihood Estimates. Adapted from NASA standards.

Likelihood					
5	5	10	15	20	25
4	4	8	12	16	20
3	3	6	9	12	15
2	2	4	6	8	10
1	1	2	3	4	5
	1	**2**	**3**	**4**	**5**

Consequence

Figure 14: Risk Thresholds.

Color	**Description**
Red	Requires immediate attention and development of mitigation strategy. Poses a direct threat to mission success.
Yellow	Risk is closely monitored. Unlikely to affect mission success.
Green	Risk does not affect mission success.

Table 4: Color Key for Risk Thresholds

6.3 Model Equations and Verification

$$F_{side} = L_f \left(cd + K_0 qd \tan\phi + \left(\mathrm{K}_o \gamma d^2 \tan\phi \big/ 3 \right) \right)$$

$$F_{blade} = c_a dw$$

$$P_p = 0.5\, K_{PE}\, (1 + a_v/g)\, \gamma d^2 W + 2cdW\sqrt{K_{PE}} + K_{PE} qdW$$

$$T_x = -F_{blade} \sin\alpha + P_p \cos(\alpha - \delta) + F_{side} \cos\beta + (W_b/g) a_h$$

$$T_y = F_{blade} \cos\alpha + W_b + P_p \sin(\alpha - \delta) + F_{side} \sin\beta + (W_b/g) a_v$$

$$T = \sqrt{(T_x^2 + T_y^2)}$$

$$L_f = d\,(\tan\alpha + \cot\beta)$$

$$\alpha_p = \beta = -\psi - \phi + \tan^{-1}\left\{ \left[\tan(\phi - \psi) + C_1\right] \big/ C_2 \right\}$$

$$C_1 = \sqrt{\left[\tan(\phi+\psi)\left\{\tan(\phi+\psi) + \cot(\phi+\psi+\alpha)\right\}\left\{1 + \tan(\delta-\psi-\alpha)\cot(\phi+\psi+\alpha)\right\}\right]}$$

$$C_2 = 1 + \left[\tan(\delta-\psi-\alpha)\left\{\tan(\phi+\psi) + \cot(\phi+\psi+\alpha)\right\}\right]$$

$$\psi = \tan^{-1}\left(a_h \big/ g + a_v \right)$$

$$K_{PE} = \frac{\cos^2(\phi + \alpha + \varphi)}{\cos\varphi \cos^2\alpha \cos(\delta - \alpha - \varphi)\{1 - \sqrt{[\sin(\delta + \phi)\sin(\phi + \varphi)]/[\cos(\delta - \alpha - \varphi)\cos\alpha]}\}^2}$$

Digging Force Zeng Model Complete Equations

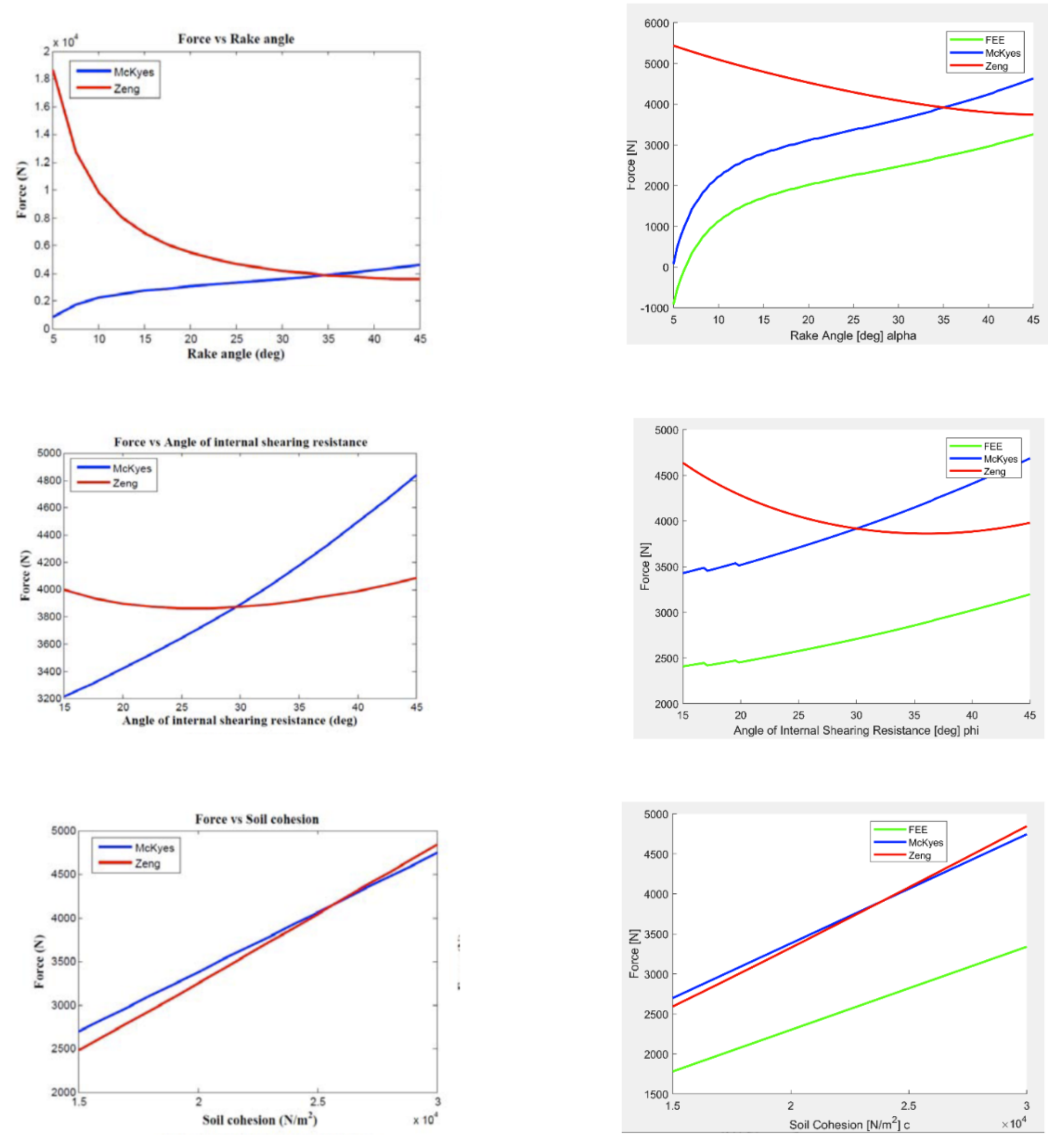

Figure 15: Digging Force Model Verification Plots vs NASA plots (left column Team, right column NASA)