Systems Engineering Paper

NASA Lunabotics Engineering Competition 2019-20

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Abstract

As NASA paves the way to the Moon and on to Mars, excavation will be a major enabler for human colonization. With the presence of water detected at the lunar poles, capturing this water is key to allow humans to exist long term. The water could be consumed, used to bathe, used for farming, or to make rocket fuel. NASA’s Lunabotics 2020 is a multi-semester university-level event that supports our Moon to Mars trajectory by requiring teams to participate in four events; Presenting the team’s robot and its design philosophy at the competition; Submitting a Systems Engineering paper explaining the methodology used in developing the robot; Performing public outreach targeting the under-served, under-represented grade K-12 students in their communities and; Design, build and compete a robot to simulate an off-world mining mission. The robot must overcome the challenges of abrasive characteristics of the regolith and icy-regolith simulant, the weight, volume and power limitations and the ability to tele-operate from a remote Mission Control Center. Our WPI Lunabotics Engineers team sought to explore the variety of ways an autonomous rover could explore and collect icy regolith on both the Lunar and Martian surfaces. Our objective was to create a unique solution that may be applied to an actual excavation device and/or payload used in a space mission. To do this, various designs for operating systems and collection devices were researched and tested in a simulated environment. This resulted in a robot capable of digging up to forty centimeters below the lunar surface while removing fine particles and collecting/delivering 8 Kg of various size rocks in fifteen minutes. Our robot is named LOADER (Lunar Omnidirectional Autonomous Digging Excavator Robot). We utilized the Systems Engineering process for efficient design and material/components from the prior years build. Solidworks models of LOADER are shown below in Figure 1.

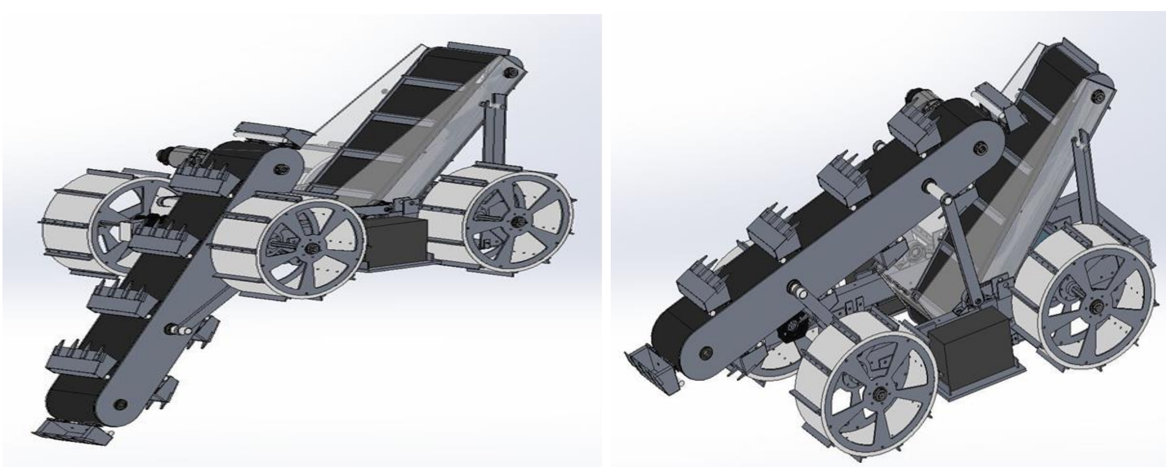

Figure 1 NASA Lunabotics WPI LOADER Mining Robot

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Introduction

The Lunabotics Team from Worcester Polytechnic Institute utilized the NASA Space Systems Engineering course materials[1] as our guide to applying our Systems Engineering approach. Our team treated Systems Engineering as the "glue" that will bring our subsystems together to form a cohesive working robot system. It not only provided a physical process for us to follow but allowed each component and subsystem to create a working hardware and software interface. Our team began by defining the Mission Requirements and Priorities. From these we developed system requirements and a system architecture which flowed down to our subsystems and component design. Each subsystem was clearly defined, and its' scope identified. We continued to follow the Systems Engineering 'Vee' Model [2] Figure 2 and the process in Figure 3.

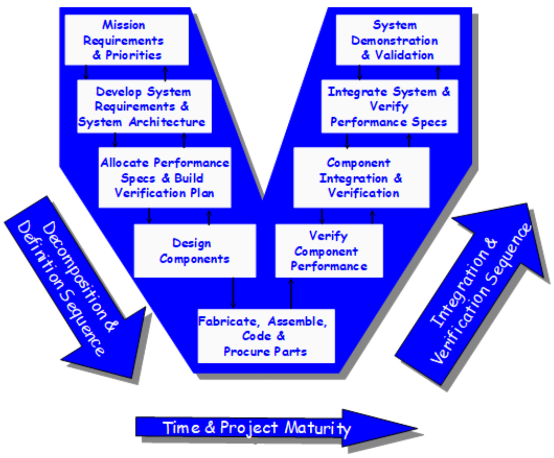


Figure 2 Systems Engineering 'Vee' Model

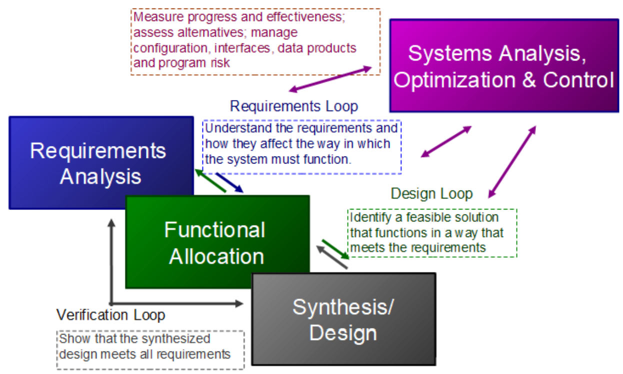


Figure 3 System Engineering Process

As Subsystems were developed into design components, we followed the Systems Engineering process. Requirements were understood and we created a feasible solution meeting design and functional requirements. As we progressed to prototyping, we found not all our digging designs preformed as expected and were not power efficient. We assessed alternatives and their risk, beginning with an auger then repeated the Systems Engineering process for a mining wheel design and a bucket conveyor. Other design goals for our robot were to be 20 Kg (33%) under allocated mass and 20% under power budget to allow future expansion of the current capabilities of the robot if the mission changes. We achieved the mass reduction and 11% margin on power budget. This paper represents our application of the system engineering process.

System Engineering Program Management

Mission Requirements and Priorities

Our Mission Objective was to create a LOADER system that successfully met mission requirements while allowing weight and power margins large enough for future enhancement. We started with volume constraints of the robot provided by the NASA Robotic Mining Competition registration, rules and rubrics. We reviewed the points allocation for the competition and designed a winning strategy. We decided to collect 8 Kg of simulated regolith per 15-minute excavation period and create a robot with potential viability for a lunar or Mars mission.

Design Improvement Criteria

Our design improvement began with reviewing the challenges and issues that prior year's robot faced. We took the lessons learned from our failures and setbacks from previous years and began to focus on optimizing past successes and redesigning our failures. The priority was to create an overall lighter robot; previous years have always had to go back and remove weight from the robot to meet design criteria. With this in mind, we are starting with a goal mass of 40-45 Kg instead of the 60 Kg specification maximum. The second improvement was to create a more versatile drive base, moving from tank treads to four large wheels. This change provided a double value. The large low mass wheels reduced the overall mass of the robot while making the drive train less susceptible to dust intrusion. The wheels will be placed in an orientation for a reduced turning radius to maneuver around boulders. The third improvement was to create a continuous digging mechanism allowing the robot to quickly pick up the icy regolith simulant and make two collection trips in the allotted amount of time. The fourth improvement was updating the robot software to optimize for the lowest bandwidth possible meaning creating a fully autonomous robot.

Design Updates

When designing the robot for this year's RMC competition we looked to the prior year's robot for inspiration and to fully understand its design issues. We understood from the beginning that the robot volume for this year's competition was drastically smaller, and we would be building a completely new base and drivetrain. We began with reviewing the drivetrain, having weight in mind we decided to change the drive train from tank tread to a wheel and gearbox design. Wheels require less power to move and are easier to maneuver around obstacles. The wheels and gearboxes will be simpler to seal against dust than the exposed tank treads. The chassis will be a completely new design to accommodate the new overall robot dimensions for this year's contest. The chassis drivetrain will only contain two brushless motors, one for each side to propel the wheels, this change allows the large heavy multi-motor tank tread gear boxes to be removed. The new design allows for a compact gearbox which provides the ability to dedicate more of the robot's volume to the primary mission of the robot, the digging mechanism. The prior year's digging mechanism was an elegant design, but we felt it was over engineered for the task at hand. It used a very complex conveyor system of buckets that both dug and dumped the payload. This system required elaborate tensioners and mandated the robot to be stationary while digging. The multiple moving parts and motors of this system had a very high mass and was hard to maintain at peak efficiently without constant adjustments. We performed trades and reviewed reliability and risk in our decision to use a new digging design. We needed three attempts to arrive at our final design. We started with an auger, moved to a mining wheel set at an angle of 30 degrees off vertical to allow continuous and deep digging. Then created a bucket conveyor that is our current digging design. Our holding bin and off loader will be very similar to last year's design using a second conveyor to offload the regolith payload. The design updates will be bin volume adjustments for required regolith volume and the offload conveyor will have a passive deployment at the beginning of a collection cycle that will allow transfer of the collected payload to an external drop off point. The passive deployment allows us to save energy and stay within the volume requirements before the match. The prior year's use of FRC electronics will be updated to a much more power efficient custom electronics design using a Raspberry Pi and Jetson Nano. We also changed our software to ROS2 and installed two cameras for autonomous operations.

Major Reviews

SRR

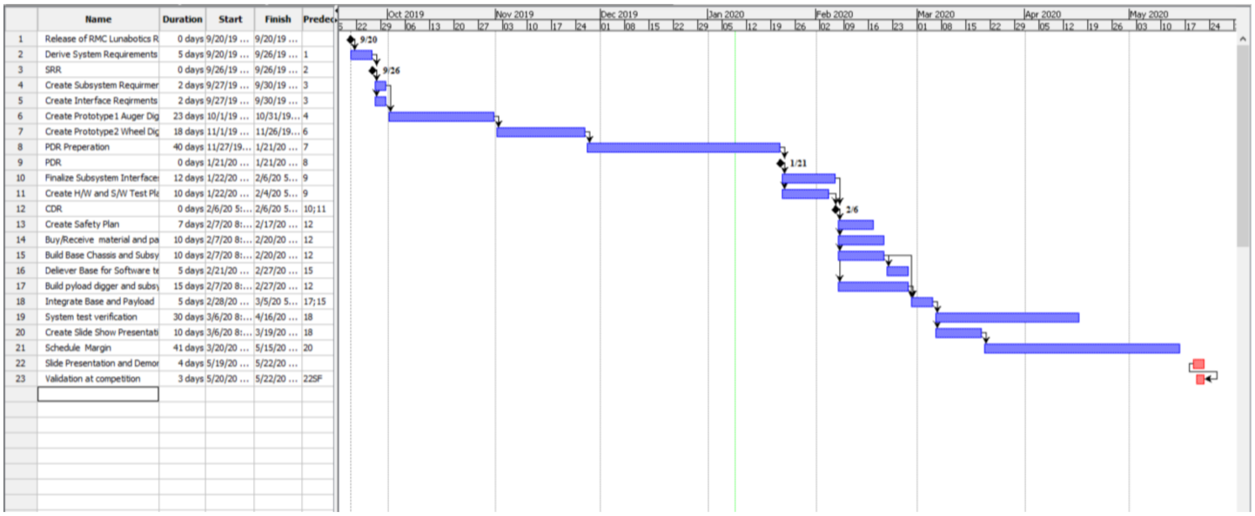
We defined the system technical requirements from the NASA'S Robotic Mining Competition (RMC) Registration, Rules and Rubrics document. After creating the requirements, a System Requirements review (SRR) was conducted to review our progress towards having all system requirements derived and defined. With the requirements understood, we could now provide a preliminary allocation of system requirements to hardware and software subsystems. This allowed the start of initial systems development and created a configuration baseline.

PDR

Our Preliminary Design Review (PDR) was conducted. We reviewed all hierarchy elements. We appraised power and mass budgets, loads and stress margins, and program risk. As we discussed how does each hierarchy element meets the requirements from the SRR, we found the auger excavator was high risk and expensive to manufacture. Due to reviewer comments we decided to redesign the excavator and hold a second PDR. Our second design was a mining wheel excavator. As we again listened to reviewer comments and found our mining wheel design did not mine regolith at a high enough rate. We then created a third design using a bucket conveyor excavator. This design met our digging depth, power draw, schedule requirements and became our baseline excavator. The PDR process preformed as expected and found challenges with our designs before we began manufacture or assembly.

Schedule

The LOADER System Engineering schedule is shown in Figure 4. Our project was not completed due to covid-19 closing WPI and NASA canceling the robot competition.



	Name	Duration	Start	Finish	Predec
1	Release of RMC Lunabotics R	0 days	9/20/19 ...	9/20/19 ...	
2	Derive System Requirements	5 days	9/20/19 ...	9/26/19 ...	1
3	SRR	0 days	9/26/19 ...	9/26/19 ...	2
4	Create Subsystem Requirmer	2 days	9/27/19 ...	9/30/19 ...	3
5	Create Interface Reqirments	2 days	9/27/19 ...	9/30/19 ...	3
6	Create Prototype1 Auger Dig	23 days	10/1/19 ...	10/31/19...	4
7	Create Prototype2 Wheel Dig	18 days	11/1/19 ...	11/26/19...	6
8	PDR Preperation	40 days	11/27/19...	1/21/20 ...	7
9	PDR	0 days	1/21/20 ...	1/21/20 ...	8
10	Finalize Subsystem Interface	12 days	1/22/20 ...	2/6/20 5...	9
11	Create H/W and S/W Test Pla	10 days	1/22/20 ...	2/4/20 5...	9
12	CDR	0 days	2/6/20 5:...	2/6/20 5...	10;11
13	Create Safety Plan	7 days	2/7/20 8:...	2/17/20 ...	12
14	Buy/Receive material and pa	10 days	2/7/20 8:...	2/20/20 ...	12
15	Build Base Chassis and Subsy	10 days	2/7/20 8:...	2/20/20 ...	12
16	Deliever Base for Software te	5 days	2/21/20 ...	2/27/20 ...	15
17	Build pyload digger and subsy	15 days	2/7/20 8:...	2/27/20 ...	12
18	Integrate Base and Payload	5 days	2/28/20 ...	3/5/20 5...	17;15
19	System test verification	30 days	3/6/20 8:...	4/16/20 ...	18
20	Create Slide Show Presentati	10 days	3/6/20 8:...	3/19/20 ...	18
21	Schedule Margin	41 days	3/20/20 ...	5/15/20 ...	20
22	Slide Presentation and Demor	4 days	5/19/20 ...	5/22/20 ...	
23	Validation at competition	3 days	5/20/20 ...	5/22/20 ...	22SF

Figure 4 Systems Engineering Schedule

Cost Budget

The LOADER system budget was fully funded for our robot build with a planned surplus. Due to cancellation of the project build and NASA competition in Florida, a large funding excess from the travel and build sections of the budget will be available for next year's WPI team to utilize.

Total funds remaining from last year			13301.46	
Total funds from mqp fund			1,250	
Total funds alloted for full team			14551.46	
	Cost per item	Quanity		
Estimated Budget				
Travel Costs				
Lodging for 7 days	$200	9	$1,800	for 9 people based on air bnb shared loging
Gas for car	$300	2	$600	
Bin Conveyor	$100		$100	
Base	$1,900		$1,900	elec900, harness100, motors300, gearbox100, wheel100, camera+mount300,metal100
Digger	$1,180		$1,180	4bar100, belt+pully+bearing80, wheel1000
charger/external control	$100		$100	
Robot total			$3,280	
LOADER Program Total total			$5,680	
Funding Margin			$8,871	

Figure 5 Cost Budget

System Engineering Method

Concept of Operation

Our LOADER robot system will be fully autonomous between all elements of the system hierarchy when operating under the environmental conditions of the competition. At the beginning of the collection event, the localization of the robot will occur with data from the depth sensing camera and IMU being transferred to the CPU. The camera processes all the images and time stamped IMU data on board to decrease CPU usage and refine depth awareness as the camera moves. The processed images are used to generate an obstacle free path for the robot to the predetermined digging site. As the path is generated the CPU directs the base drive system to follow the path. This loop continues with the camera, CPU, and the base to arrive at the destination digging site. Upon arrival at the digging coordinates the CPU lowers the digger and begins removing regolith. As the digging progresses, a sensor reading will signal the CPU when the digging mechanism reaches the desired depth of 40cm. Once this depth is reached the CPU directs the base to slowly drive backwards and continuously collect icy regolith. When 4 Kg of material has been collected a payload sensor will trigger the CPU to stop digging. The CPU will lift the digger from the ground and receive signal once the digger reaches the initial setting above the ground. The robot follows the original created path to the starting point and then moves to the regolith delivery area. The robot will unload payload until the bin sensor signals completion or 1 minute duration has passed. The process will be repeated for a second 4 Kg of regolith or 15 minutes has passed. Tele-op has also been built into the robot's operation to overcome challenges that may arise with full autonomy during the competition. Tele-op will also be utilized for a strategic advantage if the robot becomes immobilized, by using the bucket conveyor as a fifth lift mechanism to free the base if high centered on an obstacle or if the base sinks into regolith. The robots operation cycles is show in Figure 6.

Figure 6 System Operation Cycle

System Hierarchy

The major elements of the LOADER system design are provided in Figure 7. This top down breakdown will be used as a guide for the subsystems and interfaces to be reviewed at the PDR and CDR.

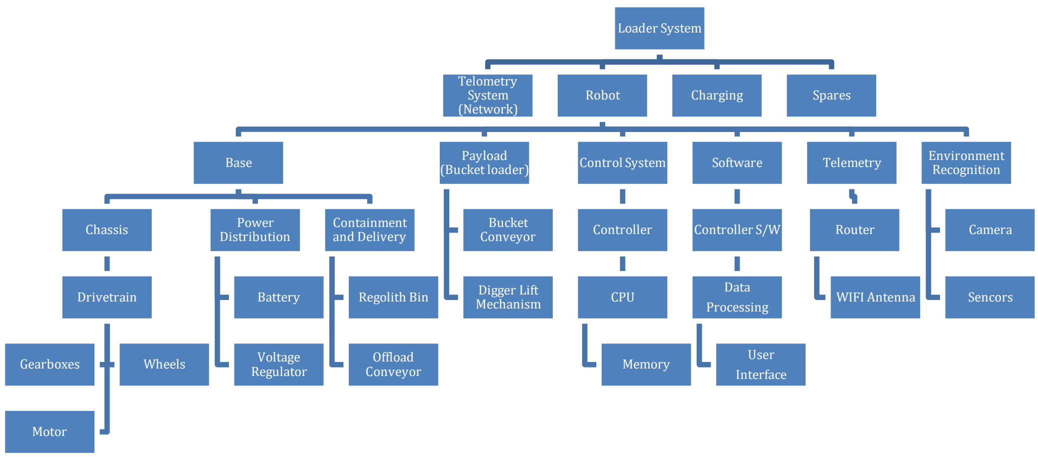


Figure 7 LOADER System Hierarchy

System Interfaces

Utilizing the system hierarchy, we can identify the key internal and external interfaces of the LOADER System. The Level 1 Hierarchy contains interfaces between the network and robot. The primary interface is not physical and occurs over wi-fi. The interface will be used for autonomous and tele-op modes. The secondary interface used for testing and practice is through a physical ethernet cable from the robot to a laptop computer. The laptop will have a controller connected through its USB port. An external charger will charge the battery after the battery is removed from the robot. Level 2 and below interfaces contain interactions between the base, payload, control system, software, telemetry, and environment recognition elements. The control system and its software have an interface with each element. The control system receives preprocessed information from the environment recognition element and its camera and sensors. The Jetson CPU uses the values from the depth image on the RealSense cameras to determine distance from the nearest obstacle. Calculations are performed and the optimal path for the robot to travel on the Jetson's GPU and this data is used by the Raspberry Pi controller to interface with the base and activate the drivetrain motors. After the calculated path is completed, the control system will interface with the payload to lower the collector and begin collecting regolith. A payload sensor will interface with the controller and signal when the collection bin is full. The telemetry element will interface with the controller for robot turn on, network connection and tele-op mode. The power distribution element provides regulated power and short circuit protection for the base, payload, controller, environment recognition, and telemetry interfaces. The base interfaces to the external bin offload area by physical location and height to deposit the regolith.

Requirements Development

We began our system requirements by describing the necessary functions and features of the system we needed to design and operate.

System Requirements

System Performance Requirements
The robot shall dig to a depth of 40 cm
The robot shall collect, hold and deliver 1 Kg simulated regolith within one run
The robot should collect, hold and deliver 4 Kg simulated regolith within one run
The robot shall be able lift the collected regolith greater than 0.5m high
The energy consumed by the robot shall be recorded with a Commercial Off-The Shelf (COTS) electronic data logger and be visible to the judges after a competition event
The Wireless Access Point (WAP) modem shall communicate with the robot
The WAP shall use IEEE802.11b, g or n standards and contain a 20MHz spectral mask

Functional Requirements

The robot shall be able to run fully autonomous or be teleoperated.
The robot shall be able to continuously dig.
The robot shall not exceed a volume of 1m by .5m by .5m at starting configuration.
The robot shall not extend vertically over 1m during operation.
The robot shall have a dust resistant enclosed electronics board.
Robot Arena Set-Up shall occur in less than 5 minutes
The robot shall not utilize a compass or GPS for path calculations

Verification Requirements

The robot shall complete one full cycle of operations including excavation and depositing the material by May 4, 2020
The robot shall meet all NASA Requirements by May 22, 2020

Other Requirements

The robot shall display an arrow marking the forward direction of the mining robot
The robot shall be completed within 9 months ending May 4, 2020
The WPI Engineers shall provide information and supplemental data about the team’s off-world mining robot as requested.

Constraints

The LOADER robot shall not exceed a cost of $5000.00

The robot mass shall be less than 60 Kg

Base requirements

Constraints

The base shall not have a mass more than 25 Kg

The base should not have a mass more than 20 Kg

Base Chassis

The chassis shall fully support the payload, control system, power distribution, and environmental recognition

The chassis shall have minimal bending when operating

The chassis shall be able to accept drivetrain components

The chassis shall accept and support mounting points from excavator payload

The drivetrain shall have at least 2 motors

The drivetrain shall provide motive force for the robot

The drivetrain shall operate on 24 volts

The drivetrain shall not stall under a 60 Kg load

The wheels shall provide enough contact area to support the 60 Kg load

The motors shall be enclosed for environmental protection

The motors shall be brushless with sealed bearings

Base Power Distribution

The power distribution shall allow battery removal for charging

The power distribution shall allow easy access for inspection and repair

The power distribution shall contain a kill switch that is clearly visible

The power distribution shall contain circuit breakers that automatically disconnect the load

The power distribution shall be environmentally sealed against conductive dust

The battery shall provide 24V and 22Ah

The voltage regulator shall operate within 2% accuracy

Conveyor Bin and Off loader

The conveyor bin shall be able to hold a minimum of 1 Kg of regolith

The conveyor bin should hold 4 Kg of regolith

The conveyor bin shall sense when empty

The conveyor bin should sense when 4 Kg is present

The conveyor bin shall keep CG in chassis frame

The conveyor bin shall be able to remove and discard regolith from icy regolith

The off loader should off load 1 Kg in 1/2 minute

The off loader shall off load 4 Kg in 1 minute
The off loader should minimize dust production while operating
The off loader conveyor shall deploy passively

Bucket Conveyor
The Bucket Conveyor shall collect 1 Kg in less than 1 minute
The Bucket Conveyor should collect 4 Kg in less than 4 minutes
The Bucket Conveyor shall not move the CG out of the drive chassis
The Bucket Conveyor shall be able to collect compacted icy regolith and BP-1
The Bucket Conveyor and power train should be environmentally resistant to dust
The Bucket Conveyor shall be durable enough to accomplish twenty 15 minutes collects
The Bucket Conveyor shall be able to dig at an angle of 40 degrees
The Bucket Conveyor shall have removable buckets allowing replacement at competition
The Bucket Conveyor shall be able operate in clockwise and counterclockwise directions

Bucket Conveyor Lift Mechanism
The lift shall be a four-bar mechanism
The lift shall contain one motor
The mechanism shall dig to a minimum depth of 40 centimeters

Technical Performance Measurement

The technical measures that supported our team achieving its Design Improvement Criteria began with optimizing past successes and redesigning prior failures. We first reviewed mass and applied a goal total robot mass of 40-45 Kg instead of the 60 Kg specification maximum mass. We allocated the mass among the hierarchy elements as seen on Figure 8 the mass budget table. Our detailed mass budget was updated post PDR. We met our design goal and achieved a 40 Kg robot having 20 Kg of margin for future additional payloads. The second improvement was to create a more versatile and efficient drive base. We allocated 4 Kg and180 amps to our drivetrain. The remainder of our power budget is provided in Figure 9. The high current motors and tank treads of the prior years' design did not meet current requirements. Using Solidworks we analyzed how much of the robot weight and volume were consumed by the tank tread and drive train from last year. We started preforming CAD trades for four large wheels with one drive motor per set of wheels. We found this was a very efficient design for power, mass and volume. This change allowed us to reduce mass with the use of wheels and lower overall volume taken up by the drivetrain. The final performance improvement was to create a continuous digging mechanism that can excavate at the 40 centimeter level while removing unwanted regolith allowing the robot to quickly pick up the icy regolith and discard silty regolith.

	Mass Budget						
System	Element	Subsystem	Component	Estimate Kg	Est Total Kg	Actual CAD Total Kg	Margin to Req Kg
Robot					40.2	40.45	19.55
	Base				30.7	18.85	
		Chassis/subsys sup		15			
			Drivetrain	4			
		Power Dist		1			
			Cntl Elec	0.5			
			Harness	4			
			Battery	3			
		Contain Del		2.5			
		Telem router		0.1			
		Env Recog		0.1			
		Cam Mount		0.5			
	Payload				9.5	14.3	
		Mining Mechanism		5		9.1	
		Delivery Conveyer		2.5		4.5	
		Digger lift		2		0.7	

Figure 8 Mass Budget Table

Power Budget (15min run time x 2 complete dig and offload runs) = 0.25 hour					
Element	Component	Estimated(Wh)	Operational Time (Wh)	Total Wh	
Base					
	Wheel Motor x 2	24V x 120A x 2	4320 x .083h (75% ave of peak amps)	359	Wh
Payload					
	Excavator Motor	12V x 40A	489 x .133h	64	Wh
	Four Bar Motor	12V x 17A	204 x .100h	20	Wh
	Offload Motor	12V x 29A	348 x .033h	11.6	Wh
Electronics					
	Controller		5Vx4A x 0.25h	5	Wh
	CPU RasPi 4 + Jetson		(5Vx1A)x 5 x 0.25h	6	Wh
	Router		3.9watts x 0.25h	1	Wh
	Camera x 2		5Vx0.7A x 0.25h	0.9	Wh
Total	Consumed Power			467.5	Wh
	Total Battery Output	12V x 22Ah x 2	24V x 22 Ah	528	Wh
Margin				60.5	Wh

Figure 9 Power Budget

Trade Studies and Prototyping

Normal engineering analysis was performed on our robot for software operating systems, drive motors, wheel sizing to prevent sinkage and stress loads on the 4 bar and off-loader. The major trades and prototyping that occurred on our system was with the digging subsystem. The major focus of the new robot design was developing an efficient and competitive digger. Since a new digging design was necessary for the team to successfully meet the more rigorous competition requirements, multiple design iterations were explored and traded before the final design was chosen. Our first digging mechanism design considered by our team was an auger design. This drill type digging mechanism could improve the excavating efficiency of the robot while conforming to new constraints. Our concept consisted of a screw-type auger attached to a drilling motor, the auger was encased in a cylindrical body to contain the dug material. In the case of regolith mining, it needed to include filtration layers to sort material by size and meet the depth requirement of 40 centimeters. The main issue with this design, however, was not its performance but its manufacturing. The design was not feasible due to the amount of expensive custom machining and welding required to build the auger. The team decided it was outside of our capability, cost range, and subsystem weight limit. Finally, the design would also complicate other subsystems to accommodate the unique deployment. Ultimately, it was decided to abandon this design for the 2020 competition.

After ruling out the auger payload design, an excavator bucket wheel was investigated. This concept included an angled mining wheel which would have buckets spaced about the perimeter to collect material. Compared to the auger, this design seemed more feasible in terms of manufacturing. The bucket wheel guides the material into the center of the wheel for expulsion onto a conveyor. Our wheel was tilted at 30 degrees and had to eject the material vertically against gravity. The 30-degree tilt was necessary to allow the mining wheel to dig an area out for the conveyor to move underground with the wheel. The team was able to solve how to guide the material through and out of the wheel onto the conveyor while moving against gravity. In order to accomplish this, the team optimized the design of a "bucket insert" which could be 3D printed for each bucket compartment inside the wheel. The shape of this insert is curved to allow material to pick up velocity, and it ends at a 30-degree angle to be sure the material does not slow at the exit. It allows the material to gain speed on the curved edge of the bucket, and by the time the material is at the top, it exits the wheel onto the conveyor. For prototyping our bucket wheel, we first modeled the concept in SolidWorks to portray the design as accurately as possible and created it with available materials that were laser cut and assembled. Our initial design for the excavation wheel and conveyor, which was created out of wood is shown in Figure 10. The purpose of the excavator wheel prototype was to allow for the angle of the conveyor arm to be changed. Two prototype buckets were designed and 3D printed, along with an internal insert to allow for a change in angle to guide the collected material through the bucket.

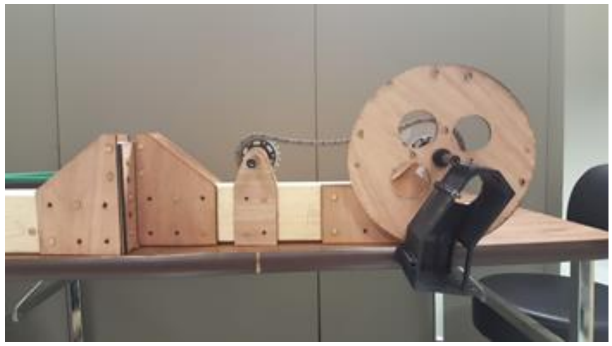


Figure 10 Prototype Mining Wheel Assembly

The two plausible 3D printed bucket designs could be attached in up to 4 spots, and the angle of the excavator relative to the ground could be altered from 0 degrees to 30 degrees with 2-degree increments. As the angle increased the effectiveness of the passage of collected material decreased. Changing from a straight bucket to an angled bucket to match the excavator wheel angles proved to be a vast improvement in both collection rate and amount. This allowed for a variety of test situations and data. Each bucket has different style teeth, angled head, and intake opening. Overall, this test method was successful in providing the team information about how much material will be mined per revolution and the feasibility of our design. Unfortunately, overall lack of mined regolith volume led to elimination of the mining wheel from mining payload consideration.

Our third and final design was a bucket excavator conveyor, where we attached digging buckets to a conveyor belt. After the design phase of the excavator conveyor, the CAD was updated to reflect the new mechanisms involved and was further developed to support motion analysis. During the CAD stage, component interactions were troubleshot; center of mass properties were adjusted through iteration and overall mass was calculated to ensure it was within limits.

To find the force required to dig through sand and rocks, at the bottom of the digging conveyor, the prototype in Figure 11 was created. This consisted of a wood base piece with a previous year's designed bucket all connected with a single axel. The base was used to secure the structure in the sand, with the bucket-mechanism able to collect a full load of material. To get the force required, a spring scale was attached to the central piece of wood. The bucket was attached in two configurations: flat, and at approximately 10 degrees. These configurations were chosen to represent the two general orientations the buckets will be in when traveling around the end of the conveyor belt.

Figure 11 Bucket Excavator Prototype

Once the digging force was determined from the prototype, it was used to develop static analyses on the bucket conveyor and four bar mechanism. These analyses provided the power requirements needed from motors and the strength requirements for the fasteners of the bucket. The prototyping phase did not include every mechanism in the robot, so the SolidWorks Analyses were a major part in showing how the mechanisms would perform in real life. Overall, the analysis phase covered each aspect of the robot using either real life models or SolidWorks data and theoretical calculations.

Reliability and Safety

We knew when we started this mining robot project that it was a high-risk operation whether mining on earth or the moon. We understand that reliability is key for a piece of equipment that is going into space. We reviewed design and operation considerations to ensure a successful competition without failure. As we appraised the elements, we came up with strategies to increase reliability. For electronics we understood that the environment can be very corrosive and conductive. Knowing this our electronics will be in a sealed enclosure with ample heat distribution. Our electrical connectors will have locks so they do not disconnect while operating. Circuit breakers will protect the battery from overdraw. Low voltage sensor will protect electronics from undervoltage. Motors will have enclosers to protect from regolith kick up. Cameras will be incased to protect from lens blockage. Connections to motors will always be soldered and coated with heat shrink to ensure a secure connection. For mechanical parts with nuts, locknuts will be used or lock tight.

Safety a key part in our engineering program, we have made multiple decisions to ensure our team and everyone around the robot will be safe. Safety began with building prototypes. When building, we always keep the work area clear of obstacles, anyone working on or near must have eye protection, and the robot will be powered off when changing software or parts. When the robot is powered the area around the robot will be restricted so non team member cannot approach the robot. Our standard protocol of announcing “Power On” before we turn on the robot so everyone in the near vicinity knows. As a safety precaution when the robot loses network connection it powers down to ensure everyone around it is safe, this is an addition to the on robot kill switch.

Risk Mitigation

The environment of regolith mining brings many risks to the functionality of a robotic mining system. A table of the pertinent risks, failure modes, root causes and their mitigations are shown in Figure 12. We listed spares on our system hierarchy, this is a form of risk management that covers multiple system elements. We will have spare wheels, motors, belts, gearbox and batteries. This allows a failed part during test or competition to be rapidly obtained and replaced. Major threats to mission success can be successfully mitigated through proper verification testing of system performance. A list of planned system verifications tests can be found in the Verification and Validation section.

Function	Failure	Potential Effects	Root Cause	Mitigation
Base motion	Robot tips	Mission failure	Center of mass moves to high	Test for ideal path & speed
Base motion	Wheels sink into regolith or lose traction	Mission failure	Low coefficient of Regolith friction or to high speed	Calculate wheel loads and add paddles to wheel
Gear contamination	Components of Gear boxes degrade	Mission failure	Regolith degrades components with repeated wear	Visual inspection and dust shields
Frame deformation or breakage	Fracture or bending	Threat to Mission success or failure	Tensile forces on members are too large	Stress analysis and functional testing
Motor	Motor burns out	Mission failure	Excessive load on motor causing high current draw.	Motor controller with encoders to prevent stalling
Base motion	A drive belt slips off	Threat to Mission success or failure	Belts lose tension or debris gets between belt and pully	Vex tensioner testing and dust enclosure
Collection conveyor	Bucket separates off conveyor belt	Threat to Mission success	Strikes hardpacked rock causing excessive load	Hinge design releases bucket upon damage
Electronics	Disconnected wires	Mission failure	Jostling of robot causes connectors to disconnect	Install locking connectors and zip tie harness
Software	Software bugs or resets	Threat to Mission success	Error during programming	Testing at component and functional level
Software	Autonomy malfunction	Loss of autonomy points	Sensor malfunction, orientation loss	Testing and redundant camera's
Electronics	Communication failure	Threat to Mission success	Poor connection, packet loss, power glitch	Watch dog timer to reset connection

Figure 12 Functional Risks

Verification and Validation

We drafted SolidWorks models for each subsystem. These models were used for stress calculations and creating engineering budgets to meet system requirements. System budgets were updated during PDR. The test program will begin with each subsystem being assembled; it will be individually tested in a custom-built testing excavating area using a regolith simulant. The results of the simulated testing will be compared to the ideal values given by the math models and our engineering estimates. Additional investigation and modifications will be made if actual values deviate significantly in comparison to calculated or estimated values.

Testing is separated into three major subsystems; Excavation Subsystem, Off-load Subsystem and Base Subsystem.

The Excavation System Verification testing will consist of: Testing the built-in mass detection systems by excavating 4 Kg of simulated material and storing in the collection bin. We will record the time required to fill the bin with 1Kg and also 4Kg of simulated material. These resultant values will be used to validate our competition timeline.

The Off-load System Verification testing will involve: Extending and retracting the off-load conveyor three times. Recording time to reach max height. We will fill the containment bin with 4 Kg of simulated regolith operate offload conveyor, record time required in order to empty bin. Verify resultant value against estimated time in competition timeline.

The Base Subsystem Verification testing will include autonomous and manual operation: Our Tele-operation System Verification will operate the robot using tele-op mode in simulated environment in order to confirm its ability to navigate, deployment of all subsystems, excavating and offloading. We will observe the robot's ability to traverse obstacles with and without material in its bin. We will operate the robot in a simulated environment while functionally testing all subsystems for 15 minutes and carrying maximum regolith, we will repeat the test for an additional 15 minutes to verify capability of two runs on the same battery pack. Upon successful completion of manual tele-op control we will proceed with autonomous systems verification. We will autonomously operate the robot in simulated environment in order to confirm its ability to navigate, excavate and offload.

Validation Testing was to occur at Cape Canaveral lunar simulation test site, this event was canceled due to covid-19.

Robot Elements and Subsystems

Base

Our robot base, Figure 13, is a major design element of our robot. We traded numerous mechanical designs that met the key requirements. Our objective was to improve the power efficiency and reduce the overall mass. We decided on a complete redesign from the previous year's tank treads by incorporating four wheels driven by two motor. This simplified design allowed us to reduce the mass, volume and power consumption of the drivetrain and base structure. The potential 19Kg weight reduction could save 19 x 1.2Mz/Kg= 22.8 million in launch cost. The design of competition wheels included multiple variations for grousers to be added to the basic wheels. The drive train will be tested at the component level and again at the Base system level when integrated to the chassis as described in the Verification and Validation section. Our previous robot used tank treads to traverse the field. Treads have more contact area with the ground than the typical wheel making them appropriate for a terrain composed of the lunar simulant by distributing the weight of the robot over a larger area. Because of this, treads prevent heavier robots from sinking into the fine simulant which can create drag, and even immobilize the robot. Treads are also able to manage obstacles without the use of a suspension. Unfortunately, treads are not as effective at maneuvering when compared to conventional wheels, and this was one of the numerous reasons the team considered when deciding to go with wheels. Along with greater maneuverability, wheels are lighter than treads, which has become a key factor considering new mass constraints. Using wheels therefore allows weight to be allocated into other sub-systems such as the digging mechanism. The second advantage of wheels is space. Given the size of the drive chassis, treads would use up over half of the width of the chassis. Finally, wheels provide speed, light weight (compared to treads), and overall maneuverability. The team also believes that wheels will be easier and faster to produce. To improve maneuverability, grousers are added to each wheel, as this increases forward motion performance. We chose to use 12 grousers, at 30 degrees to keep multiple grousers in contact with the soil at once.

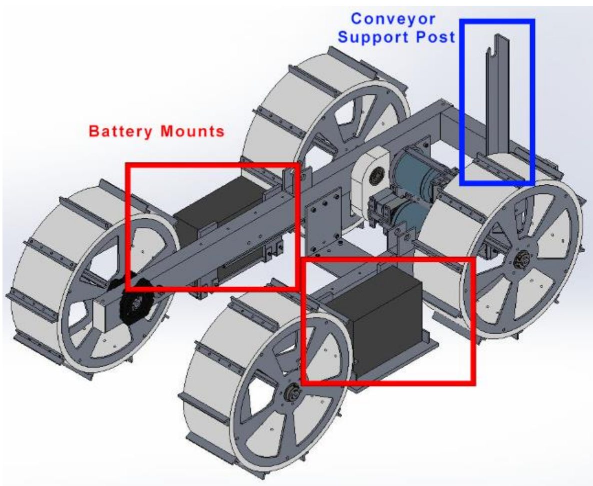


Figure 13 LOADER Base Design

Electrical

The Base power distribution system consists of two 12V 22Ah batteries in series. This capacity has 11% margin over our required 467 Wh for the 15 min regolith collection. The electronics of LOADER are distributed into different voltage lines and data transfer lines as shown in Figure 14. The Jetson, Raspberry Pi 4 CPU, and Hero will be encased in an aluminum enclosure with a removable lid for protection against the regolith dust. The enclosure will also perform double duty as an aluminum heat sink for the electronics. The energy consumed by the robot will be recorded with a COTS electronic data logger and be visible to the judges after competition. The competition requires an emergency kill switch. Our robot contains five motors, two 24V motors in the drivetrain, three 12V motors, one each, for the bucket conveyor, the four bar and the offload conveyor. The drivetrain motors are both controlled using an ODrive motor controller that allows fine tuning of PID, easy compatibility with ROS, and limits the current provided to the motor. The bucket conveyor motor is controlled through a CAN bus, beginning with a Hero Board and ending at the voltage regulator module. Two Talon controllers regulate the voltage to the four-bar and conveyor motors and send data from the encoder back to the Hero Board. There are four sensors: a potentiometer, an IMU, and two IR sensors. The potentiometer is connected to one link of the four-bar mechanism. It can read the position of the four-bar at any given time. The IMU is used to determine if the robot's tilt angle is too great in situations such as driving over a rock or entering a crater that is too steep. Finally, the two IR sensors are used to check how much material is in the collection bin. If neither sensor is providing a signal for a given amount of time, it is assumed that the bucket is empty. If the upper sensor provides a signal, the bucket is full of icy regolith.

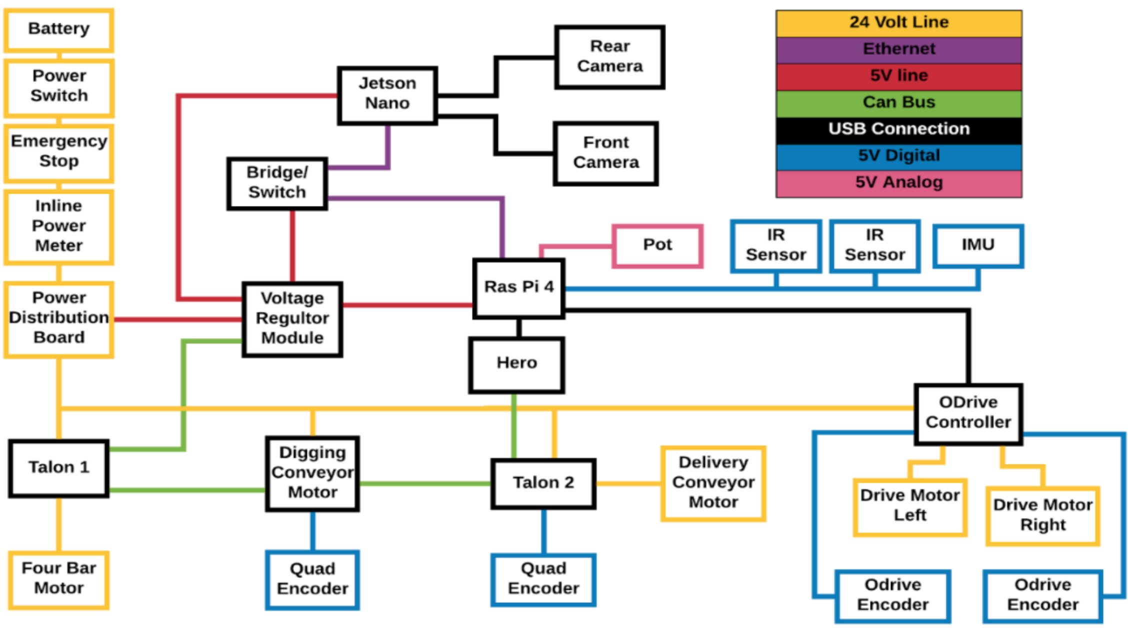


Figure 14 Electrical Layout

Collection Bin and Offload Conveyor

In the past years the robot has had a conveyor system to offload the regolith material. This method has been tested and proven to work in the past so we will be utilizing it for this years' competition. Our bin and offload conveyor assembly is shown in Figure 15. The conveyor will make up the bottom of the collection bin. The conveyor bin can remove and discard regolith from icy regolith using the screed slits on the rear of the bin and the conveyor grouser entry door. The door allows the grouser to pass through and as the door is lifted the regolith is expelled but the icy regolith is retained. The assembly will passively deploy to a height suitable for offloading the collected regolith to the external collection bin. This conveyor design was chosen over an auger offload design because an auger cannot remove 100% of the regolith from the bin.

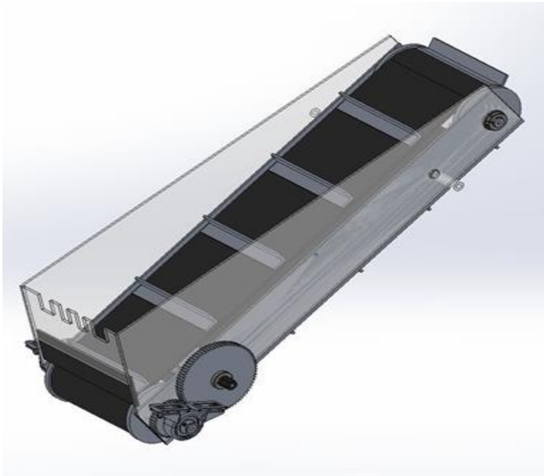


Figure 15 Offload Conveyor

Bucket Conveyor Excavating Payload

This digger consists of the conveyor system, its motor, ten excavating buckets, and secure fasteners. The belt system that was chosen is a sturdy polyamide profiled belt and pulley with a customizable size. The decision to go with a belt instead of a chain was based on the amount of surface contact provided by the driven pulley to the belt which addresses issues with chain systems such as slipping or falling off sprockets due to debris buildup. An issue in the past with other conveyor excavators was the radius of the pulleys which was difficult for the buckets to maneuver about. Due to this, the pulley chosen for LOADER was maximized. The conveyor is powered by a Falcon 500 motor. Due to the high power this motor provides and customizable gear stages, it can be geared based on required torque determined during testing. The bucket design was based on the tested Markhor buckets which were already built and available for use. Some features of this design that will be reused include the durable machined bucket teeth and the general shape of the sheet metal. The fasteners on the buckets include a hinge and bump system to aid in revolving around corners, as well as strong screws designed for the custom belt which can withstand 170N of perpendicular force.

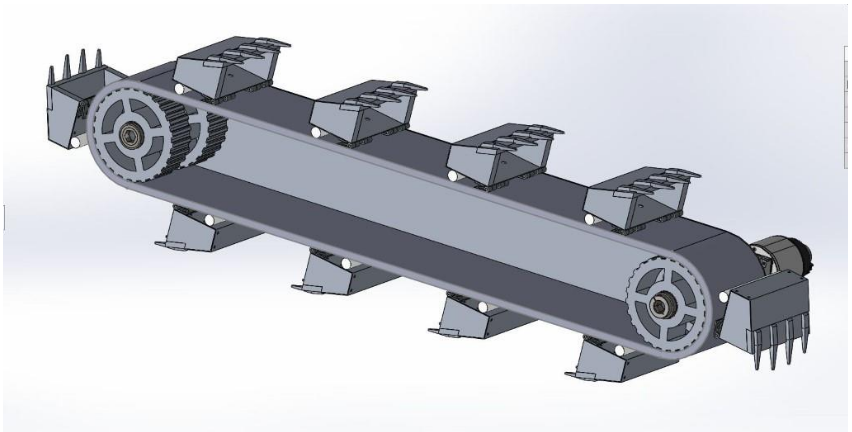


Figure 16 Bucket Conveyor

Software, Control and Environment Recognition

This year, the team used the Robot Operating System (ROS2) to control our robot. With ROS2, we used an action-based communication environment to send and receive data from the sensors on the robot. The decision to use ROS2 was supported by several factors. First, ROS is a standard in robotics. This means that there is widespread support for many of its capabilities and will therefore be much easier to work with. It will also be easier for future teams to onboard, assuming it is more likely that they have worked with ROS2 rather than any other framework. ROS2 has support for a variety of libraries that are geared towards completing common robotics tasks, navigation for example. In order to maintain efficient use of bandwidth the team encapsulated much of the complexity of our system. The visual subsystem was removed from the ROS network, thus encapsulating all the raw visual data communications into a node that will only communicate processed data across the network. At the beginning of this project, the main processor on the robot was the Nvidia Jetson Nano. The Jetson is optimized for image processing and has a dedicated GPU. However, aspects of the Jetson prevented the computer from being fully utilized. When it became clear that the Jetson was not capable of handling image processing as well as central communication, the team began to look for a replacement. To decentralize the ROS network, optimize our connections to the rest of the sensors, and encapsulate the area of highest data traffic, the team decided the Raspberry Pi 4 was a better main processor.

The Lunabotics competition offers three different ways to complete a collection: Teleoperation, Partial Autonomy, and Full Autonomy. When competing with full autonomy teams earn five-hundred more points than with full teleoperation. Not only does this provide a motivation for using full autonomy, it is also reflective of real-world applications when communicating with rovers on other planets. Due to the distances between Earth and other planets, the signal time for the robot to receive commands from Earth are so delayed that the robot could not be properly operated in real time. Using autonomy will allow the robot to control itself and make decisions that could not be done in the timeframe of teleoperation, therefore operating under more realistic conditions.

According to the rules for the Lunabotics Competition, the robot must travel to the digging site while avoiding different obstacles on the field. This requires us to use multiple different methods of tracking and image recognition techniques to be able to track obstacles. For this, we will be using the NVIDIA Jetson Nano and the libraries OpenCV and OpenVSLAM to provide environment recognition and map the environment. To view the field, we will be using two Intel RealSense D435i Depth cameras, with one camera each in the front and back of the robot. This system takes images from three different kinds of cameras: an RGB, infrared, and depth. The RGB image displays what would be perceived by the human eye. This will allow the robot to be teleoperated, giving a driver the ability to see the environment from the robot’s view. The infrared camera will allow the robot to see in the absence of visible light. Lastly, the depth camera will allow the robot to calculate the distance from a point on the image. The depth aspect of this camera is the most important because the depth data will be used for localization and mapping algorithms that will determine the pathing of the robot. Combining the orientation features that the fiducials can give with the depth processing of the RealSense cameras; the robot will be able to determine its exact position relative to the fiducial. This is very beneficial for alignment with the collection bin to ensure that LOADER will deposit collected regolith into the collection bin. Using the rear RealSense camera’s RGB imaging, LOADER can properly align with the collection bin via a fiducial placed on the bin.

For control we will utilize Controller Area Network (CAN) instead of Pulse Width Modulation (PWM). Compared to the PWM protocol, CAN allows for the sending and receiving of messages to and from each component on LOADER, whereas PWM can only send integer values (0 to 255 generally). This was an important feature due to the Talon SRXs having built-in encoder ports that the team wanted to utilize. In addition, CAN could be used to send an operating voltage or amperage for each motor instead of a speed percentage to run at.

An inertial measurement unit (IMU) will allow the Raspberry Pi to collect orientation data for the robot. Through the use of an IMU, LOADER can determine its initial orientation on the field, as well as direction of motion and other forces applied to the robot.

An ethernet communication system was chosen to tie each component together and connect to the Wi-Fi bridge. The team chose the ethernet standard over other standards, like Wi-Fi or Bluetooth, to diminish the possibility of signal interference. In addition to avoiding signal interference, theoretical transfer speeds were greatly increased due to the nature of Ethernet.

Appendix

[1] NASA Space System Engineering course materials www.spacese.spacegrant.org

[2] Systems Engineering 'Vee' Model pg16 of Introduction Module:What is Systems Engineering in NASA Space System Engineering course materials www.spacese.spacegrant.org

[3] A Traditional View of the Systems Engineering Process Begins with Requirements Analysis page 15 of Introduction Module:What is Systems Engineering in NASA Space System Engineering course materials www.spacese.spacegrant.org