Pathbuilder

2021 NASA X-Hab Academic Innovation Challenge

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Project Purpose

The Pathbuilder project is a North Dakota State University (NDSU) undergraduate investigation into the design of a rover that would be suitable for lunar construction and is funded through the NASA X-Hab challenge. X-Hab is a portion of NASA that challenges students to act as a new set of eyes and design engineered solutions that address critical needs of the Artemis program. The goal of this specific project was to design, build, and test a prototype of a lunar rover called the Pathbuilder. The Pathbuilder rover is a solar powered tele-operated rover that can create flat, compacted regions on the lunar surface for the purpose of creating roads, habitat foundations, or launch pads. Due to the large complexity of the project, it was assigned to four senior design groups within the NDSU Mechanical Engineering and Electrical Engineering departments. These groups include an excavation team, drivetrain team, structure team, and electrical team. This report will detail the information, findings, final design solutions, and testing that have been made by the structure team during the fall and spring semesters of the 20/21 academic school year.

The project started with research into current solutions pertinent to the success criteria as a general idea which was then followed by a refinement of the success criteria. Next, design options to fulfill the success criteria were researched. After research was completed, conceptual designs were presented as viable solutions to the finalized success criteria. With the aid of a screening process the best designs were advanced for presentation to all Pathbuilder teams. After the presentation of subsystem concepts by all teams, overall rover designs were made based off the compatibility options. A final design was selected based off a process that utilized both screening and scoring matrices. Additional analysis was conducted afterwards to verify if the chosen design would be technically and structurally sound. Once the design was finalized, all parts were ordered and manufactured either in house at NDSU or at 3rd party manufacturers.

Structures Team

The structures team is responsible for a variety of subsystems within the rover including the frame, regolith hopper, solar array structure, and thermally controlled electronics enclosure. The structure interfaces with many other subsystems, so frequent coordination with the other teams was required throughout the design and assembly process.

The success criteria for the structures team are as follows. Designing a mechanical frame that can support all static and dynamic loads that may occur during any process of operation of the rover and is able to withstand any unpredicted loads to a reasonable degree. Designing a hopper that can hold regolith to increase compaction weight and can dispense regolith for cut or fill operations. Designing a solar array structure that can move the solar panels to maximize solar energy collection in different scenarios. Designing a thermal control system that can keep all electronics and batteries within operational temperature ranges.

Design Problem and Objectives

To provide a functional rover that meets all performance criteria established for the Pathbuilder criteria several project objectives were established to address all problems that needed to be addressed by the structures path builder team. From a large perspective the structures component of the project needed to provide a physical frame that would allow for attachment, mounting, loading and operation of elements under any realistic environmental conditions that the rover could encounter. It was decided by the group that the best approach to address the numerous problems that needed to be addressed was to systematically break down the problems and solve them with semi-independent subsystems.

The structural integrity of the rover was the most crucial element addressed by the team as its performance would dictate the outcome of all other elements. The problems that the frame had to address was both dynamic and static loading caused by the attachment of various subsystems, in addition the frame also needed to shield and guide electrical wiring. The frame accomplished this by utilizing both square and angle aluminum pieces to provide a high moment of inertia and favorable structural stability.

The solar array was one of the defining subsystems of the Pathbuilder projects as its autonomy was one of the unique features about this excavation rovers design. Being that the rover is dependent on its own collected power an efficient system was of the upmost priority. To maximize the solar collection of the rover and allow for solar collection in any environment the rover may encounter a diverse moveable solar collection system was deemed necessary. A solar mechanism with both 360-degree rotation about its vertical axis and the ability to tilt the panel from a position of 90 degrees to the horizontal to at a minimum of 45 from the horizontal. The tilt and rotational features were established to be capable of collecting a maximum amount of sunlight in areas of the moon from its pole to 30 degrees latitude. According to solar collection theory, the maximum collection of sunlight occurs when the incoming sun beam is normal to the collection surface. The maximum collection criterion shows the importance of the ability of the solar ray to articulate when the rover is on an incline or the rover is positioned with the sun at a non-regular angle to the rover.

In addition, the collection of sun by the solar panel the reduction in panel efficiency caused by dust accumulation was a major concern. To prolong the life of the rover a dust removal system was deemed crucial to the longevity of the rover. To be deemed successful a dust removal system must be able to remove enough accumulated dust for the panel to be able to provide enough power to continue operations. As a general guideline 80% dust removal from a heavily covered panel was desired.

A critical element of the Pathbuilder Rover is to be able to shuttle regolith to and from different locations on the moon, as well as compact the regolith on the lunar surface. As such, an assembly must be designed to be able to reliably contain regolith and increase the compaction potential of compacting devices. These properties must also be designed around design constraints such as size, and potential interface issues. To efficiently shuttle regolith, the size of the design must be maximized. Maximizing the holding size will also increase the amount of weight the rover may store, therefore also increasing the compaction potential. The size will be dictated by how much weight will be required for significant compaction. Additionally, the design must maximize size while also being able to interface well with other rover components. The method of regolith disposal is also a key aspect of reliable shuttling of regolith. The disposal method must allow enough clearance from the ground to allow the rover flexibility in different dispensing situations. It should also rid the rover of all regolith, with minimal regolith leftover. Finally, similar to the sizing of the design, the disposal method must not interfere with separate functions of the rover.

A final problem that the structures team addressed was the problem of storage and protection of the electronics. An electronics enclosure was designed and manufactured. Constraints included the available space within the existing frame, and the requirement that the enclosure be big enough to contain the battery and all other electronics. The enclosure also had to be able to protect the electronics from dust within the operating environment. In addition to the objective of containing and protecting the electronics, the enclosure had to be designed to include a thermal control system that would keep the temperature of thermally sensitive electronics within their specified operating temperatures.

Detailed Design Documentation

Solar array

The solar array had several key elements that needed to be completed to ensure the functionality of the project that include, the tilting mechanism, the rotational mechanism, the dust removal system, and the supporting structure of the panel. All the elements that went into the construction of the solar assembly were evaluated and scrutinized as was listed below.

Yaw Mechanism

To provide rotational motion of the solar panel a stepper motor was used to modulate the rotational position of the motor. The torque required to rotate the panel was determined to be the torque required to rotate the panel when the panel is at a maximum moment having the mass horizontal to the central shaft. A three-dimensional rendering of the yaw mechanism can be seen below in Figure 1.

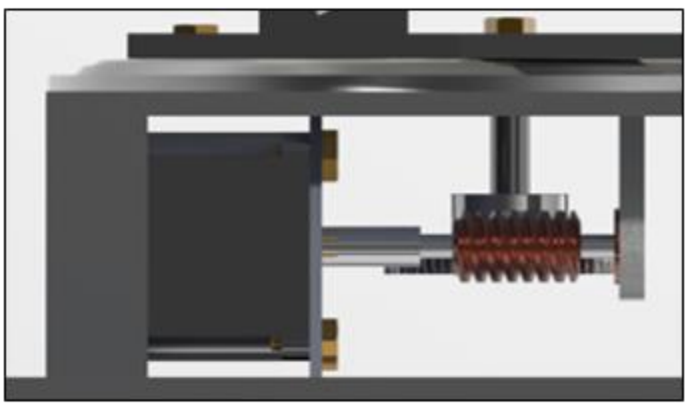


Figure 1: Yaw Render

A 60:1 worm gear was favorable because it provides a high torque ratio was compact and has a natural self-locking mechanism that prevents back feeding. In addition to the stepper motor a potentiometer was outfitted to the solar panels rotational axis to provide 1:1 reading of the position of the panel to the electrical team. A potentiometer selected had an internal memory that would preserve the location of the panel after the event of a loss of power.

A prefabricated steel shaft that attached to the stepper motor via a flexible helical coupling. The coupling was implemented to reduce the manufacturing of the project and provide more forgiveness on gear mountings by allowing more movement in the mounting shafts. The coupling was rated at 27-inch-pound which was over five times the required torque to be deliver from the stepper motor to the worm. To provide additional support and decrease the deflection and the potential of having the gear assembly bind a bearing was press fit and mounted in opposition to the stepper motor.

The horizontal work gear powering the system meshed with a vertical shaft that had a gear that was to mesh with the worm gear. The system was attached to the rotational element off the panel by means of a machined coupling that utilizes a set screw to secure the position. This element transferred the rotational motion to the solar panel array which in turn would rotate on a turn table mounted to the top of the solar gearbox and therefore rotate the panel.

Tilt Mechanism

The original design of the tilting mechanism of the solar panel consisted of a linear actuator with an attachment point located near the midpoint of the panel to provide a tilting force to the panel. In addition, the geometry of the panel was determined by selection of the mounting positions. This design resulted in the selection of a 3A, 1500 N linear actuator with a 30 cm stroke that would allow for the panel to be rotated from 30° to more than 90°.

The rationale behind this design is the same of that as the rotational features of the array as it would allow for optional panel placement. After subsequent issues with panel vendors the original panel was subbed to a less expensive and lighter panel. As a result, the loads that were calculated resulted in an additional increased in the safety factory of the system. The position of the solar panel and governing feedback to its maximum and minimum position was government by two limit switches that would be tripped when the panel position passed a specified maximum or minimum angel. It should be noted that the determining factor to the position of the solar panel for maximum solar collection was determined by the electrical team such that the average values of four photoresistors located on the corners of the panel could be used to determine what tilt and rotation adjustments would be needed to accomplish the maximum solar collection. Three-dimensional CAD renderings of the solar panel array can be seen below in Figure 2 and Figure 3.

Figure 2: Solar Panel CAD, Side View

Figure 3: Solar Panel CAD, Angle View

Dust Removal System

Due to the high static and dusty environment commonly found on the lunar surface the dust system was designed to sever as a semi-permanent solution to prolong the life of the rover. Four air nozzles were selected for the design to provide proof of concept for the design rather than full functionality. The nozzles were selected from a catalog in which the output air flow, throw distance, exit velocity and consumption were determined by a specified supplied pressure. The rest of the system was designed with components to satisfy the catalog’s air requirements with no component having an allowable operational air pressure less than 890 kpa. The air was stored in a PVC air capsule that was pressurized using an air compressor. From the tank a ball valve was inserted as air flow regulatory device and as a safety feature. Subsequently a solenoid value was in place to provide remote control of the dust removal system when needed. The solenoid valve fed into an air manifold that distributed the flow to the four nozzles. The air nozzles were positioned on the panel to maximize the effectiveness of their air burst delivered to the panel. Dust control system can be seen below in Figure 4.

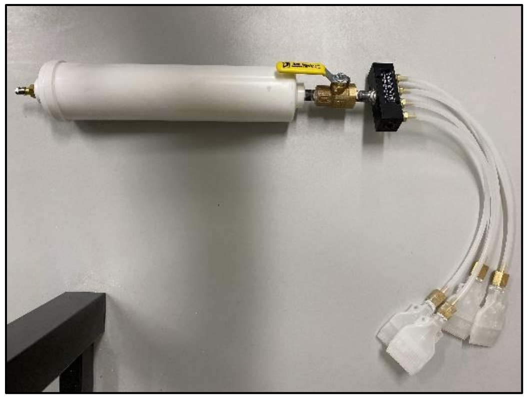


Figure 4: Dust Removal System

Panel Support

A frame was constructed around the panel to provide a solid point of contact between the actuator and the solar panel without providing any potential harm to the panel while load is being applied. The frame was designed to protect the edge of the panel on both its side and a portion of its bottom face. The panel would be bolted to the frame and a crossbar was bolted to the frame to provide a contract point for the linear actuator. The frame also served as a mounting point for the hinge connection located on the bottom of the panel to allow for the rotation of the panel. The last major function the panel support has was to serve as a place to mount the dust control elements to the panel by providing reinforced mounting points.

Design Verification

Finite element analysis (FEA) was used on critically loaded components on the rover to ensure their performance under stress is acceptable. The frame of the solar panel itself was considered of adequate strength; under the assumption the manufacturer did their due diligence for the panel’s structural integrity. The results of the FEA analysis can be seen below, figures 5-A and 5-C show the mounting plate and figure 5-B and 5-D show the cross bar that carries the load to the rest of the rover frame. Both the mounting plate and cross bar are constructed of 6061 aluminum. The test parameters for the FEA analysis were conducted with a load of 270 newtons which was initially a safety factor of 1.5 if the loading will occur at earth gravity. However, with the change in panel vendors the wight was reduced significantly to provide a safety factor of nearly 3. Under lunar gravitational conditions, the safety factor would be approximately 18 because of gravitational differences. These findings suggest that for lunar applications the design can be significantly reduced.

The results of the FEA analysis showed that a maximum deflection of .09237mm and stress of 10.89 mpa. These maximum conditions were found to occur in figure 7-B and 7-D which depicts the cross bar of the solar array. A deflection of .09237 mm is not great enough to cause any concern for rover functionality. Because the base of the solar panel is solely a structural support any piece alignment is not needed therefore this deflection causes no concern for final performance. For the deflection to cause interference a deflection of 3 millimeter should have to occur to cause interference with the turntable.

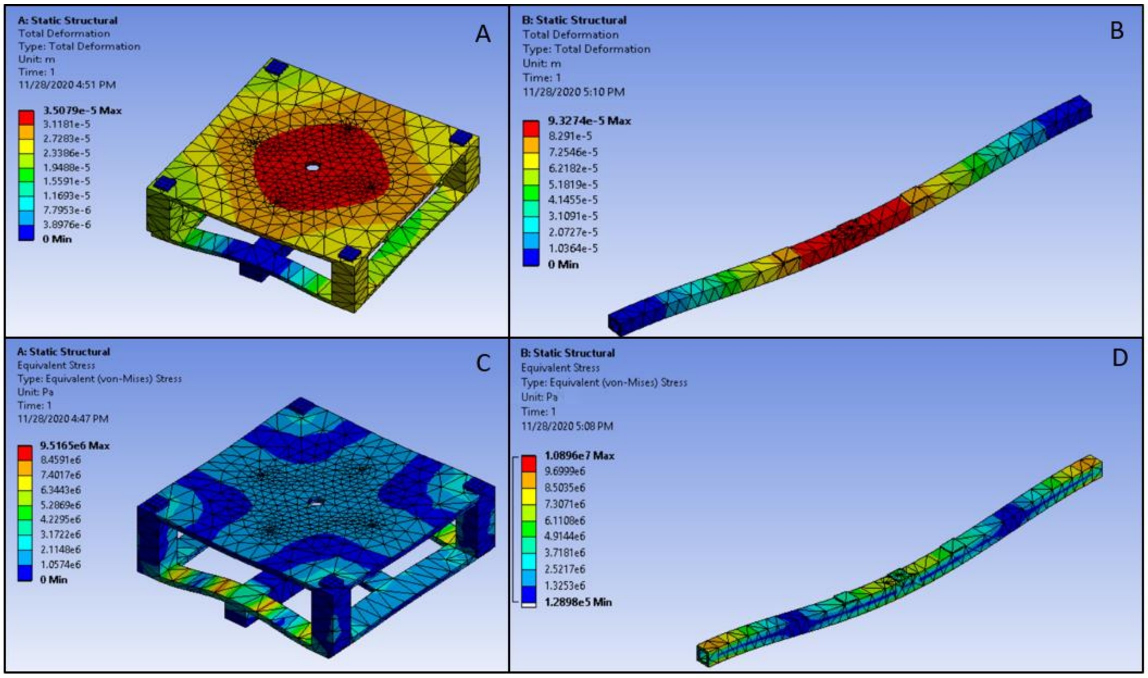


Figure 5: FEA Results

The supporting base of the solar stutter was also evaluated using FEA. Initially it was determined that the base of the of solar array would have a deflection of 5.79mm as can be seen in 6-A. To minimize the total amount of deflection in the base an iterative approach was used as can be seen in 6-B and 6-C. Designs see in figures 6-B and 6-C have a deflection of 2.06mm and 1.38mm, respectively. Design C was selected as it had the least amount of deflection of the frame.

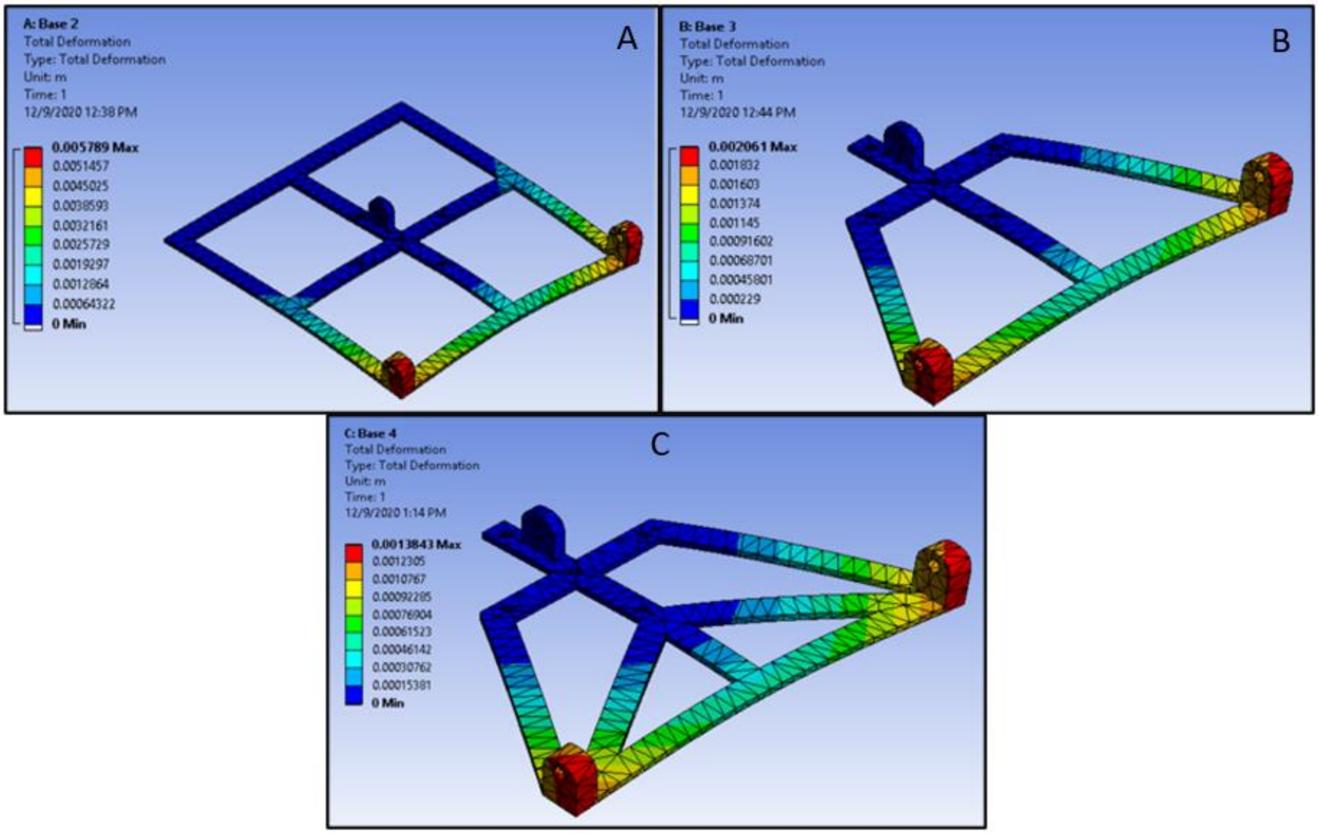


Figure 6: Solar Base FEA Results

FEA analysis was used to evaluate the safety of components that were expected to have significant stress or to ensure the alignment of gear and bearings would not be compromised. The results of the FEA analysis impacted the design of the model as was described. With the conclusion of this topic the detailed design documentation is finished for the solar array.

Regolith hopper

To serve the purpose of displacing regolith, a regolith hopper design was implemented. The hopper allows the rover to shuttle regolith to and from locations on the moon, while also providing significant weight to the rover, thus increasing the compaction potential of the roller system. Many design considerations were analyzed, regarding the size, geometry, disposal method, and ability to interface well with the other structural components. Dumping systems such as hopper conveyors and dump trucks were analyzed for their disposal mechanisms and viability for the rover.

After continuing with a conveyor belt style hopper, additional research was conducted in order to further develop the design. Multiple conveyor belt styles were considered, including a bucket conveyor and pan conveyor. The most useful design aspect from the bucket conveyor is the bucket configuration. The buckets of the conveyor efficiently hold the regolith for transport. However, this bucket configuration limits the capability of dispersing the regolith across the entire length of the conveyor.

Inspiration was pulled especially from the pan conveyor. The pan conveyor is a heavy duty, chain driven conveyor, with small compartments, called the pan. This conveyor is designed especially for abrasive material, much like the regolith that the hopper will be containing. Another benefit of this design is the walls of the pans of the pan conveyor as they can better contain material inside the conveyor. The downfall of this design is how difficult it is to implement into the rover; the pan conveyor is too large, heavy, and difficult to manufacture. To remedy this, design aspects of the pan conveyor was combined with that of the bucket conveyor.

The resulting conveyor belt is one that utilizes cleats, as depicted in Figure 7. The geometry mimics the bucket conveyor in that it will help contain the regolith. The design also borrows the continuous design aspect of the pan conveyor. Because the cleats are directly attached to the belt, there are no openings in which the regolith can slip. Additionally, a conveyor belt tension assembly was designed such that the belt may be passively tensioned remotely. This is a key feature of the conveyor belt system, as temperature effects may change the tensioning of the belt. The tensioning system utilizes two, four-inch springs on either side of the conveyor belt with a strength of 46.1 lb/in. Utilizing these springs ensures that the belt stays in tension regardless of wear as well as the ability to adjust accordingly without manual interference.

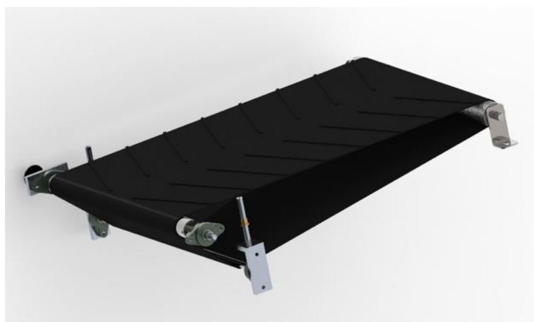


Figure 7: Hopper Conveyor CAD

Certain configurations of semi-trucks and trailers utilize a conveyor belt discharge system also served as a design inspiration for the regolith hopper. These trucks feature high-capacity beds for foods such as potatoes and corn. The length of the conveyor belt is limited and cannot span across the width of the rover. Because of this, the sides of the hopper had to be angled inwards to funnel the regolith onto the conveyor belt, depicted in Figure 8.

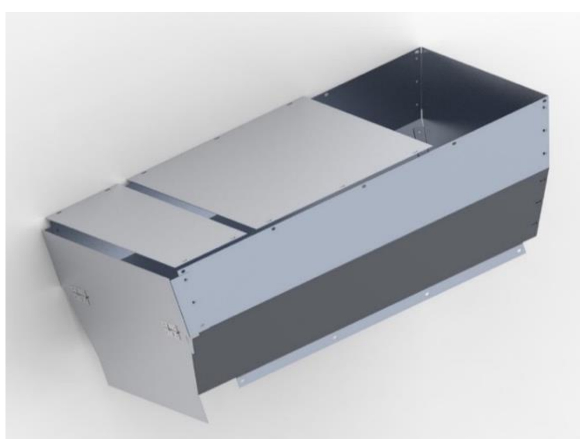


Figure 8: Hopper CAD

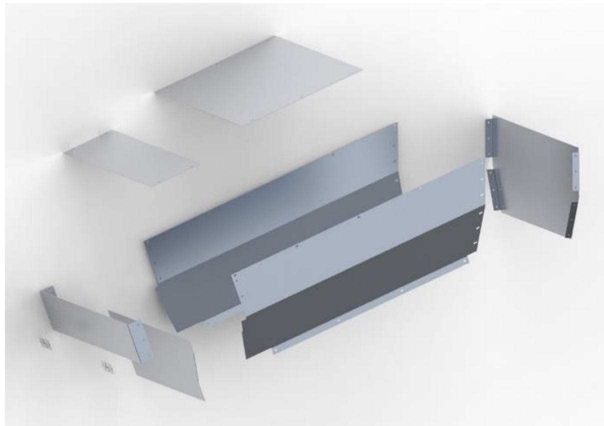


Figure 9: Hopper CAD Exploded

Early designs of the hopper featured a fully unibody structure with each panel welded together. This design proved unfeasible due to the insufficient material thickness for welding. The use of welds also greatly degrades the strength of the material. Instead, the hopper was split into separate components as depicted in the exploded view of the hopper in Figure 9. The use of separate paneling also improves the interface ability of the components. It will be easier to attach these components to the frame as separate pieces. The material chosen for the panels was 5052-H32 aluminum, based on its lightweight properties, strength, and material availability.

A door was designed such that the regolith would be contained while the hopper was not in use. This door utilized self-closing door hinges. These spring hinges will keep the door shut, while the rover is maneuvering and filling the hopper. When the conveyor is activated, the cleats of the conveyor push the regolith into the door and allowing the regolith to be dispensed. At full capacity, it was estimated that the hopper could contain about 330L of regolith. At full capacity, this hopper can hold up to roughly 4,700N of sand on the moon, or about 800N of regolith on the moon.

To ensure that the conveyor belt can dispense the regolith, a proper motor must be selected. The motor must deliver the proper amount of torque to the belt in order to overcome the frictional force of the belt on the frame. For this calculation, a friction factor of 1.2 was applied to the belt onto the metal frame. This factor is an estimation based on previous testing and documentation [1]. Using this factor allows for a conservative estimate on the friction force necessary to operate the pulley. The operating torque required to turn the pulley at full capacity (entire volume of the hopper) was about 24.62 N*m. This value factors the force of gravity on the moon, rather than the earth.

Design constraints were also applied according to the limitations of the controller. Initial power constraints, according to the Electrical team, were a maximum controller output of 12V and 2A. Because of this, the original power configuration utilized two gear motors on either side of the conveyor drive shaft. This would have been a difficult configuration to work with considering the need for the motors to be aligned and timed properly.

Instead, the Electrical Team obtained new motor controllers capable of 12V and 3A. This increase in current allowed for the purchase of a 516:1 gear motor from andymark. This motor, at 3A of current is capable of delivering about 15N*m of torque. This, coupled with a bevel gear configuration shown below, exceeds the amount of torque necessary to turn the pulley at full volume.

The design process resulted in the following hopper assembly depicted below. This assembly features all of the components featured in the design process, such as the aluminum hopper body, conveyor belt, belt tensioning system, and gear motor. The picture also depicts the interface between the frame and the drivetrain sub-assemblies.

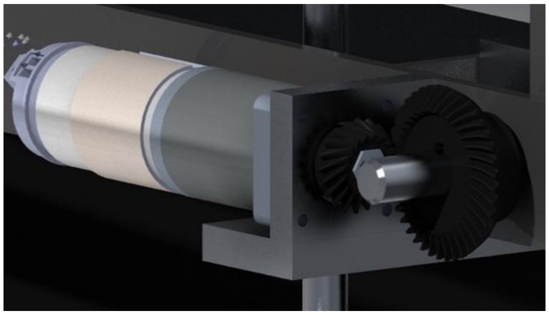


Figure 1: Hopper Conveyor Bevel Gears

Figure 2: Assembled Hopper Conveyor

Design Verification

To verify the structure of the design, Ansys FEA analysis was conducted for the hopper frame. A static load of 4702N was applied to the hopper structure. This weight is the estimated load of sand at full hopper capacity. Additionally, a safety factor of 1.4 was applied along with the maximum angle, resulting in a maximum deformation of about 1.4 mm of deflection on the sides, and 20 mm on the front, depicted in Figure 12. This was seen as a reasonable amount of deformation of the hopper sides, allowing it to retain is shape and form in order to properly function. The front of the hopper however, undergoes a significant amount of deformation. This will be helped with the support of the electronics enclosure. This ensures that the hopper does not interfere with other systems, such as the conveyor belt or solar array, when under max loading.

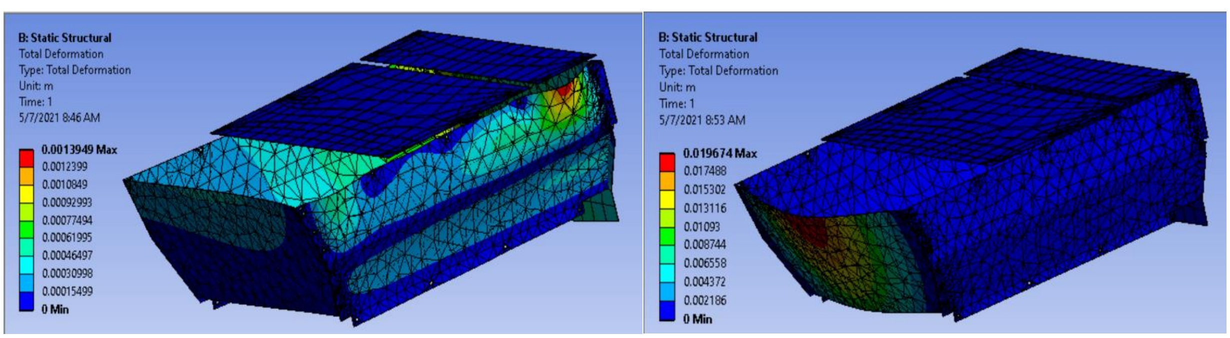


Figure 32: Deformation of Hopper

Under the same loading, the stress of the hopper was also analyzed. The equivalent stress experienced by the hopper under full loading resulted in a maximum stress of 312 mpa. Comparing this to the yield strength of 193 mpa for 5052-H32 aluminum, determines that the aluminum paneling will yield under extreme loading from the sand. However, this is considering max force conditions, when the hopper is fully tilted on its side. Under normal operation the hopper would remain upright when containing regolith, and only a minor angle applied when traversing the lunar surface. Under this circumstance, it is reasonable to assume the hopper will remain intact under normal operation and loading.

Additionally, these testing conditions were used with the assumption of operation on earth. Considering the gravity of the moon, the aluminum paneling may be reduced in thickness even further to reduce the overall weight of the hopper as well as the launch weight, if the rover was being used for operation on the moon.

Frame

The structural and technical integrity of the overall rover design relies heavily on the strength and geometry of the frame. The frame is required to support all static loads from mounted equipment as well as dynamic loads of any mining operations or movement. The frame also must fit all of these components properly to ensure each subsystem can function correctly. The main function of the frame is to support all tensile, compressive, and shear stresses being applied to it either from excavation operations or from the weight of the equipment itself. Because the rover will be tested on Earth, the frame must be designed to support its weight on Earth, rather than about 1/6 its weight as it would experience on the moon. The frame is also expected to have enough interior space to accommodate all the equipment it is carrying.

Based on the other subsystems chosen for the final design from all groups as well as the rough sketch of the final rover design, the initial CAD model shown in figure 13 was created. This design utilized 2” x 2” Square aluminum tubing with ¼” thick walls on the lower portion of the frame, while 1” x 1” tubing with 3/16” walls were used for the vertical struts and upper portion of the frame. This was done to provide the most load bearing potential to the points of the rover that were expected to have the highest loads, such as the lower perimeter of the frame where the drivetrain components would attach and most of the weight of the rover would need to be supported. Smaller tubes were chosen for the upper portion because much smaller loads, primarily coming from the solar array and possible dynamic forces from the regolith, would be applied that could be supported with smaller tubes. The 1” x 1” tubing was also chosen to support directly underneath the hopper and regolith loads. While this is where most of the weight of the rover is, use of five smaller tubes would provide enough load bearing potential, making use of 2” tubes unnecessary. These tubes were also oriented front to back to allow the hopper conveyor belt to slide smoothly along its surface without getting caught in the grooves between the tubing while it moves.

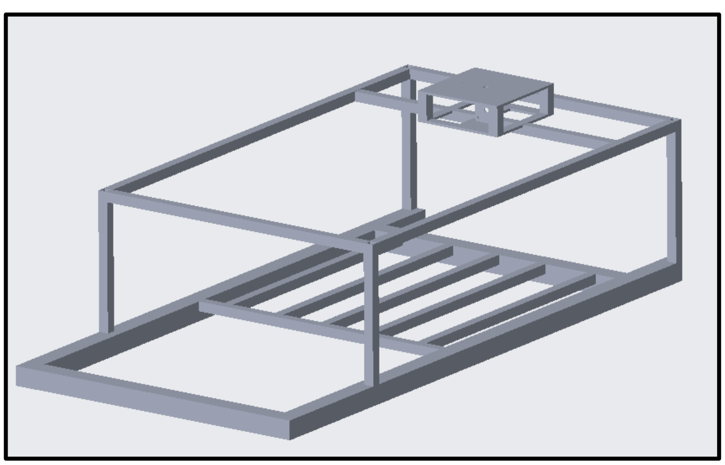


Figure 4: Original Frame Design

Concerns over the feasibility of welding all components together and discussions with manufacturing staff at NDSU resulted in many of the aluminum tubes used for the initial frame design to be replaced by similar sized aluminum angles. This design, seen in figure 14, is geometrically the same as the original, except that the 2” tubes along the bottom portion of the frame and the 1” tubes on the top portion were replaced with similarly sized angles. Use of angles allows for members to be drilled into each other rather than welded, making manufacturing simpler and faster, and it also reduces the weight of the frame significantly by cutting out nearly half the material of the original frame. Because aluminum angles to not have the same bending strength as full tubes, the 1” tubing supporting the hopper and solar structure was not changed as these portions will be supporting the most weight.

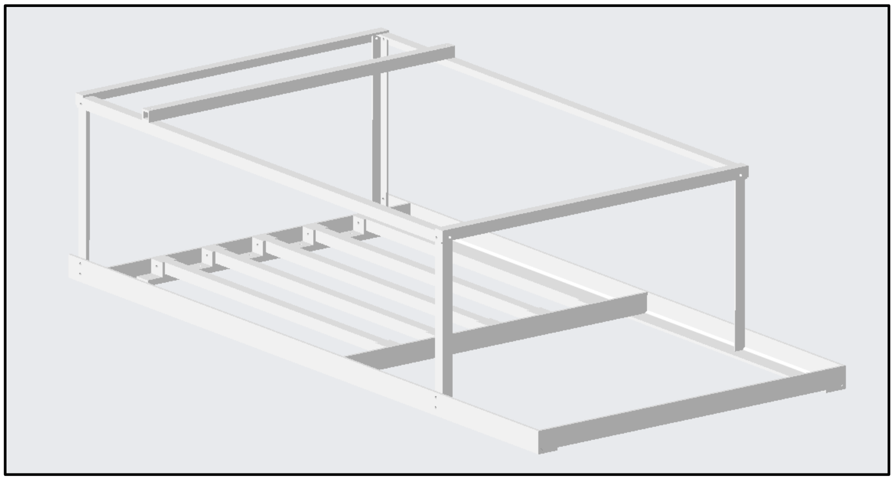


Figure 14: Final Frame Design

Design Verification

Critical elements of the frame were analyzed using FEA with the program Ansys. Analysis of the solar panel base as well as the cross bar supporting it was done during solar analysis and was determined to be structurally sound. The main loads being applied to the frame come from the mass any stored regolith in the hopper. The load applied to the bottom portion of the frame was estimated to be approximately 4,700 N, assuming a full dump bin and with Earth’s gravity. Figures 15 and 16 show the deformation and stress of the frame, respectively. A distributed load was applied to the center portion of the frame with supports on either side representing the support the drivetrain will provide the frame.

The maximum deformation that the frame would experience with a full load is .61mm with a maximum stress of 53 mpa. This minimal deformation would not have any adverse effects on the overall integrity of the frame and would not interfere with the function of the hopper conveyor. The 53 mpa maximum stress applied is also well within the 1.5 safety factors of the yield strength of aluminum 6061 (221 mpa).

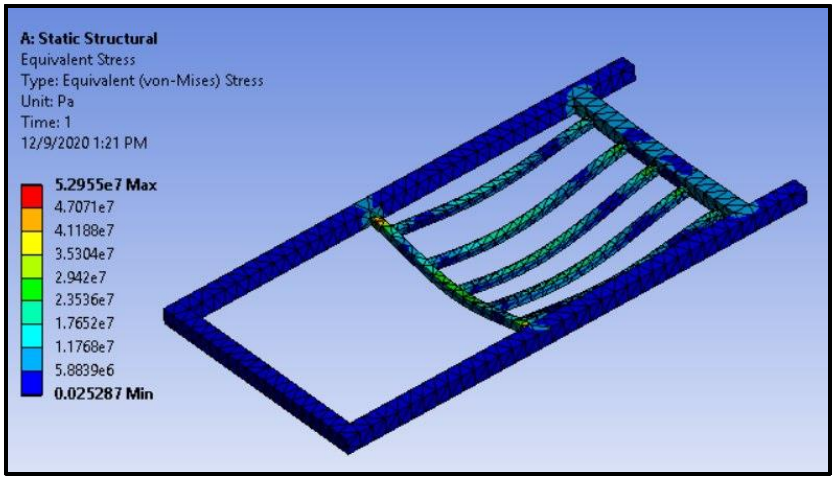


Figure 15: Stresses in Frame

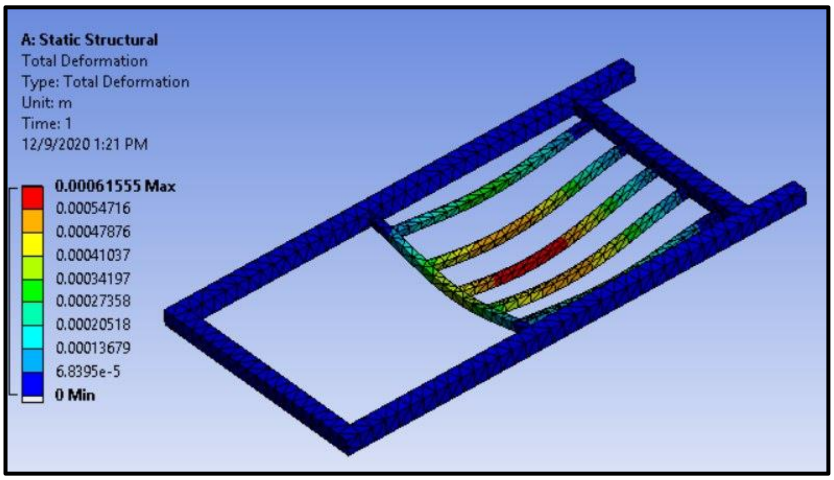


Figure 16: Deformation in Frame

Laboratory Test Plans and Results

Solar array

Three major elements of the solar array were tested for their individual performance, additionally a full-scale operation was desired to evaluate the performance of the rover however was unable to occur due to problems that arose in other subsystems of the path builder project and time content related conflicts. The elements of the solar system that were tested independently was the yaw system, the tilting mechanism, and the dust control system.

The yaw system was tested by sending control commands to the stepper motor. The stepper motor was able to take commands of rotating the panel by 90 degrees. The panel was able to rotate along the path and complete the delivered command. A few notes to make on the rotation of the panel and the performance of the test. The locking mechanism that held the shaft of the gear that meshed with the worm was a little oversized. The results of this manufacturing error would result in the gears central axis being slightly of centered to that of the panel array when the worm gear is tightened. Additionally, there was some instability in the worm gear as it was positioned in a long cantilever position at times creating issues with the alignment of the yaw mechanism.

The tilting system was evaluated by testing the performance of the linear actuator and its response to controls. The linear actuator was able to move the panel across its full design range when power was applied to the actuator. The power consumption of the actuator was significantly less than that was predicted with the actuator only requiring a current of 1 A to move the panel across its design range.

The dust system was tested independently and was the most extensive test preformed for the testing of the solar panel. To protect the solar panel a pane of glass was used instead to simulate a dust covered panel. The pane of glass was covered with 6 mm of raw flour as a fine particle simulant. The dust removal apparatus was positioned at the far end of the glass pane as can be seen in Figure 8. The air canister was pressurized to 75 psi and was discharged using a ball valve that was positioned inline to the air stream. The results of the dust removal test can be seen in Figure 17. It can be seen that all of the flour was removed from the panel for the first 430 mm of the panel and particulate was found up to 1700mm from the base. This performance was satisfactory to the removal criterion for the dust removal system.

Figure 17: Dust Removal on Glass Pane

Regolith hopper

The hoppers' ability to contain and dispense regolith were aspects of the design that were tested. The hopper conveyor was tested by sending power to the driving gear motor. When powered under no load, the belt is able to be driven with no apparent difficulties. When loaded, the hopper conveyor was able to accept a certain amount of weight before the belt would slip from the drive pulley. This was tested by pulling on the belt as it was being driven by the motor. It was observed that, with enough force, the belt would disengage from the pulley. The motor did not show any signs of stalling from the increase of load. Instead, at higher loads, the pulley drive shaft tended to shift and disengage the teeth of the gears. A solution to this may be to tighten the set screws of the bearings to help lock the shaft in position. However, a better solution would be to include a spacer in between the gear and the frame in order to lock the position of the shaft.

Frame

The primary testing done on the frame was structural testing to ensure there was no excessive deflection of the members that would lead to structural failure. Loads of 100lbs were placed on each of the hopper support beams and no deflection was able to be measured. The cross beam that supports the solar structure was tested by placing the solar panel on the beam to check for deflection. No significant deflection was seen in the cross bar, but the 1" angles supporting the cross beam and solar panel did deflect, so an additional cross beam support was added underneath the solar structure to distribute weight more evenly along the 1” angle.

Drivetrain Team

This drivetrain must provide sufficient traction to ensure that the rover does not become immobile during terrain leveling operations. The drivetrain must also provide stability to ensure that the rover does not tip over during operation as well as provide adequate ground clearance to drive over small rocks.

The drivetrain must be able to operate using a 12-volt system and no individual motor must draw more than 2 amps. The size of the rover frame should be within a 120cm by 80cm rectangle. The height limit of the drivetrain is not specified but should be kept as low as possible. With the drivetrain attached to the rest of the rover, the rover must be able to withstand a 45° tilt in any direction.

Detailed Design Documentation

Powertrain

The goal of the powertrain sub-system is to connect the wheels of the rover to the wheel support sub-system, as well as drive the wheels. The wheels must also be driven at an appropriate speed so that rover is able to have enough torque to drive over and around obstacles. The goal of powertrain was to output enough torque needed to drive a 200kg rover up a 30° incline.

The most impactful constraint on the powertrain was the low wheel speed calculated to be approximately 10 RPM. Most small DC motors have a free speed greater than 5000 RPM, so a large gear ratio is needed to lower the output speed. Ground clearance was also considered when designing the powertrain so that rocks can be driven over. A 12V, 5A operational power limit was given by the electrical design team. Encoders also needed to be integrated into the powertrain system to allow for more precise wheel control. The powertrain sub-system must also include a hub for the wheel to rotate around and carry loads transferred from the wheel to the frame.

Hub Design

The design of the hub system incorporates an outer hub that mounts to the wheel and an inner hub that mounts to the wheel support system. To support the loads from the wheel and to allow for low friction rotation, the inner hub was designed to have two deep-groove ball bearings seated on the outer surface of the inner hub. The two bearings have a locational interference fit following ANSI B4.2-1978 standards. The deep-groove ball-bearings can take small thrust loads transferred from the edge of the outer hub and rim, as well as all the radial loads transferred by the outer hub.

The outer hub was designed to slide over these bearings and be bolted to the inner face of the wheel. The material for the inner hub was chosen to be 7075 aluminum so the hub would be lightweight and easy to machine, but still be strong enough to prevent premature ring gear teeth wear and bending when supporting the weight of the rover. The outer hub was chosen to be 3D printed using PLA material.

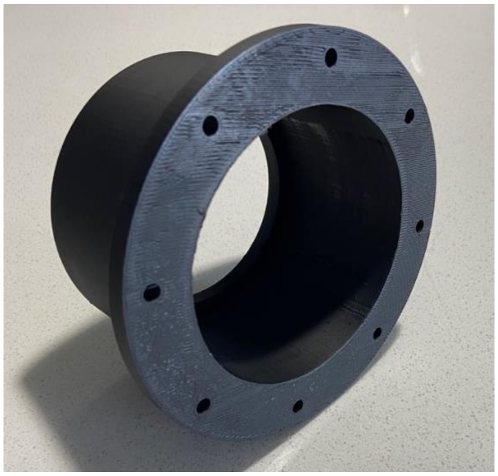


Figure 18: Outer Hub

Figure 19: Inner Hub with Bearings and Gearset

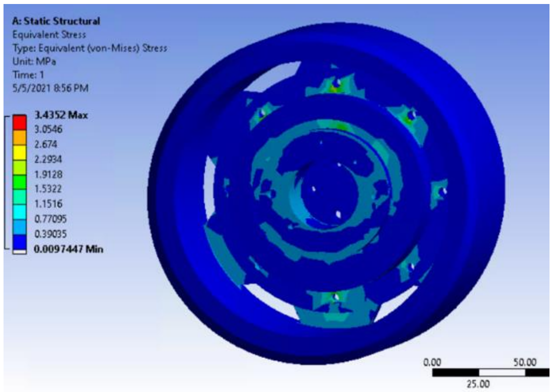


Figure 20: Stress Analysis

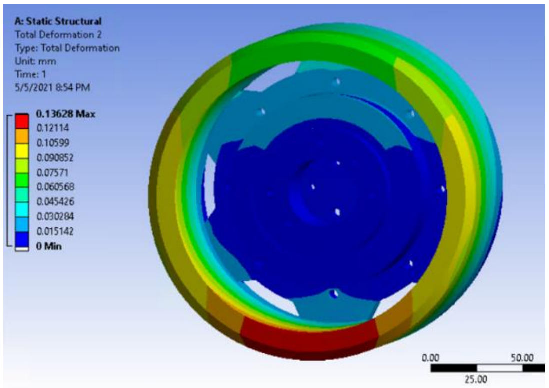
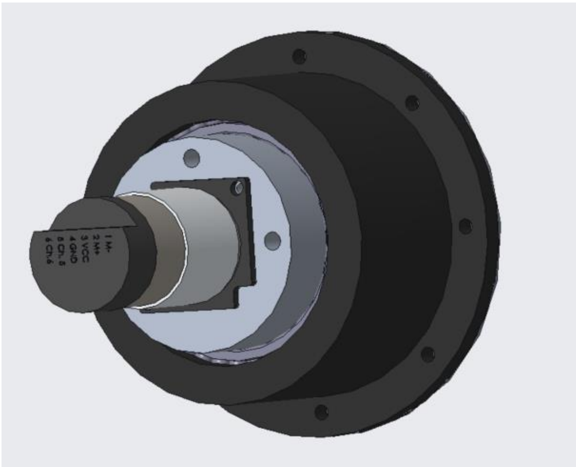


Figure 21: Deformation Analysis

Once the final CAD models were created and materials were selected, FEA analysis was performed using ANSYS Workbench. The model in ANSYS was set up similar to how the wheel would be assembled in real life, with the outer hub being attached to the wheel using the matching bolt hole patter on the wheel and outer hub and bearings between the inner and outer hub to transfer loads. A 500 N loading was applied in the positive Z direction to the bottom of the wheel, while the face of the inner hub was held fixed simulating it being attached to the wheel support. The analysis found the max stress to be 3.44 MPA and the max deformation to be 0.136 mm. The results did not find any problem with the part geometry or material selection.

Gearbox Design

To create the large gear ratio needed to achieve low wheel speeds and high torque, a planetary gearbox was chosen because planetary gearboxes can create large gear reductions and the output of the gearbox lies on the same axis as the motor shaft. Having the motor, gear reduction stages and wheel all lying on the same axis eliminates the need for idler shafts and extra bears thus reducing weight and complexity.



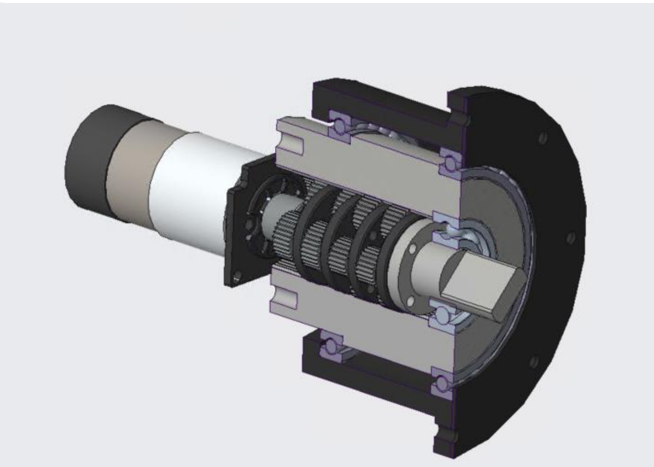


Figure 22: Gearbox and Wheel-Hub Combination **Figure 23:** Cross Section of Gearbox and Hub Combination

The final design included a 4-stage planetary gearbox that is integrated into the hub of the wheel shown in Figure 22. Integrating the gearbox and wheel hub together allows for a smaller overall length for both components which leaves more room in the center of the rover for driving over obstacles or excavating. Using an estimated rover mass of 200kg, the moment needed on each wheel to drive up a 30° incline can be calculated.

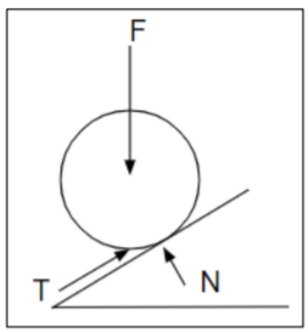


Figure 24: Loadings on a Wheel on an Incline

When using the diagram above the value for T is found to be 250-N at each wheel. The moment needed to drive the wheel can be calculated to be 38-N*m. Using the torque of the selected motor at 5A, 0.03-N*m, a gear ratio of 1266:1 is needed to achieve a moment of 28.575-N*m. Using the failure torque of 100-N*m for the planetary gearsets from vexpro, a factor of safety of 3.5 can be calculated for the gearsets. A 4-stage gear reduction was used in the initial design and using the available gearsets the closest available gear ratio without going below 1266:1 was 1296:1. Using the motor free speed of 6600RPM, wheel size of 12" and gear ratio of 1296:1 a rover ground speed of 3cm/s was approximated. To transfer the torque from the gearsets to the wheel an adapter was designed to mount the motor to the inner hub, a vexpro Versa mounting block was attached to the motor and then bolted to the inner hub using the two 10-32 holes machined.

Gearbox Adapter Design

To transfer torque from the gearsets to the wheel, an adapter was made using 7075 aluminum. The adapter was made to mount to the last 4:1 gearset in the planetary gearbox by press-fitting pins into preexisting holes that were made to have 4mm pins pressed into them. The flat faces of the adapter would slide into a slot machined in the wheel to transfer torque to the wheel. During design of the planetary gearbox, it was also determined that an extra bearing would be needed to support the end of the gearbox adapter to prevent the adapter from moving radially within the gearbox causing the gearsets to bind. The mounting face width of the adapter was designed to allow the total amount of play in the gearbox to be roughly 1mm. This allowable amount of play in the gearbox allowed the planetary gearsets to move slightly fore and aft about the central axis of the gearbox and prevented binding due to friction between the gearsets. To create the adapter, a manual mill was first used to make all the cylindrical features of the adapter, then a manual mill was used to make the flat faces. After creating the flat faces, an indexing head and mill was used to create the 4 holes for the pins to mount to the last gearset. Extra time was taken to make sure that the bolt circle was centered to prevent vibration and binding during rotation of the gearbox.

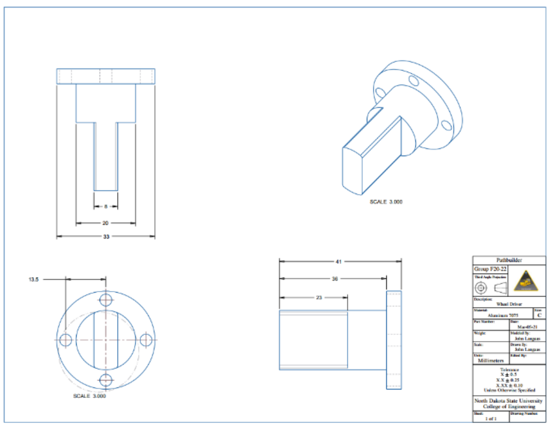


Figure 25: Drawing of Gearbox Adapter

Figure 26: Render of Gearbox Adapter

Wheels

The main design objective for the wheels is to provide enough traction force to make the Pathbuilder rover more stable when driving and working on excavation. Wheels are the point of contact with the surface. Unlike the situation on the Earth, the wheels of Pathbuilder cannot be replaced when they are broken. Thus, another constraint of the wheels is the durability. The goal of the designed wheels is to have higher tractive capability, increased weight capacity, and extended life.

By the report of Mars Exploration Rover, we have found the rovers experience numerous of slip-on certain terrain, which may cause the task to fail or slow down the progress of achieving the goal. Thus, slip ratio is a key element to use to determine the state of the rover and to perform control. The slip ratio can be defined as $s = wr - v$, where v is the actual linear velocity, w is angular wheel velocity, and r is the wheel radius. This equation also can be normalized as $s = \frac{wr-v}{wr}$. In order to make the rover travel stable, we need to maintain a slip ratio of around 0.15.

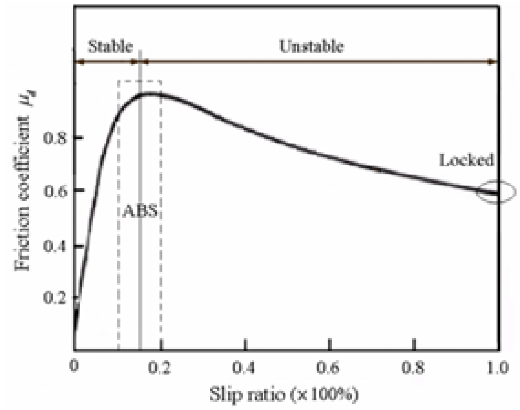


Figure 27: Variation of Frictional Coefficient to Slip Ratio

The pressure-sinkage is another important variable of rover, especially since the Pathbuilder will do a lot of excavation work. To determine the pressure-sinkage while the Pathbuilder is not moving, we use the Bekker's formula, $p = \left(\frac{k_c}{b} + k_\emptyset\right) h_s^n,$ where p is static stress, b is wheel width, k is displacement under the wheel, c is cohesion stress of the soil and φ is internal friction angle of the soil. After some formula derivation, we eventually will get formula, $h_s = r(1 - cos\theta_s)$, where h_s Is sinkage while Pathbuilder is not moving and θ_s Is the tire-ground contact angle. For the pressure-sinkage when the Pathbuilder is moving, h_k Can be modeled by $h_k = c_2 s$, where c_2 is soil restitution ratio.

The team decided to use a PVC pipe and PVC plate to make the rims and use conveyor belt as the tires. The reason PVC material was chosen was its strength, to support the weight of the rover, and PVC plastic can be easily glued. The conveyor belting will be used as tire treads. The wheel will be mounted on the hub and driven by the DC motor.

The PVC pipe that was selected was size 12, which has a 289mm inner diameter and 323.5mm outer diameter. The thickness of the pipe was 17.4mm, to match the thickness of the pipe, the PVC plate chosen had a 19mm thickness. PVC has good tensile strength 5600 to 6700 Psi, and excellent impact strength, 10-18 ft/lbs./in. The temperature range of those PVC is -18◦C to 71◦C to maintain the best performance. The PVC pipe was cut using a band saw, and the PVC plate was manufactured using a CNC machining center. On the PVC plate, there needed to be 8 5mm⌀ holes and an 8mm wide slot. Those 8 holes are for mounting the wheel to the hub, and the slot is for driving the wheels. The width of the wheel is 190mm, and weight of each PVC rim is 9kg.

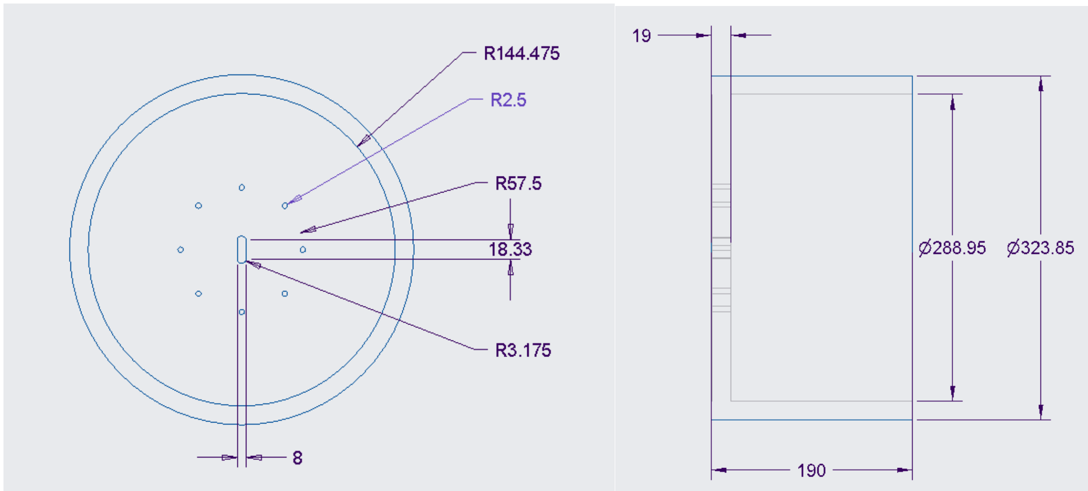


Figure 28: The Parameters of the Rim

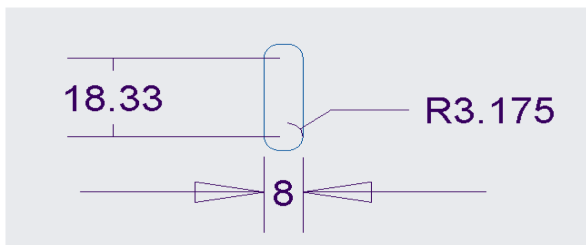


Figure 29: The Parameters of the Slot

The conveyor belt that chosen was “Cleated Belting for Roller-Bed Conveyor.” The thickness of the belt is 7.9mm and the height of cleat is 6.3mm. The belt was cut using a utility knife to 190mm wide. Bolts and nuts were used to fix the rubber tread on the rim. Each tire weighs 2.2kg, and the total weight for one wheel is approximately 11.5 kg.

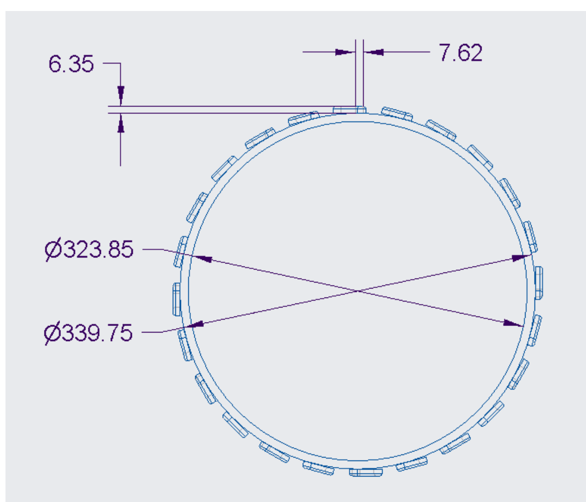


Figure 30: The Parameters of the Tire

Wheel Assembly

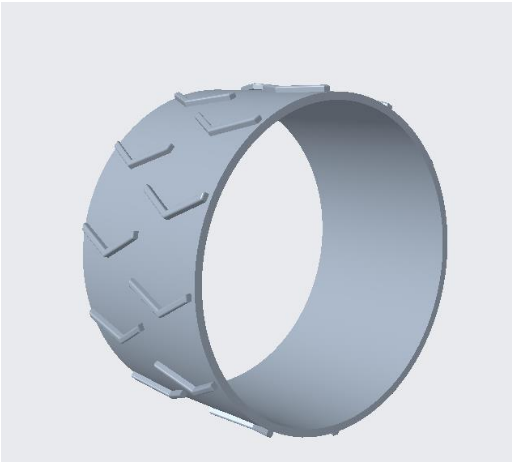


Figure 31: Tire

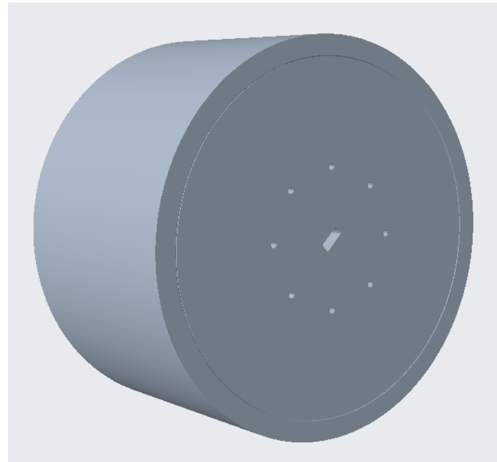


Figure 32: Rim

Figure 33: Final Wheel Model

Figure 34: Manufactured Wheel

3Drivetrain frame

The frame assembly is the bridge between the traction subsystem and the rest of the rover. The frame carries the weight of the rover while in motion and while static. The lunar surface poses a unique challenge in traction because its surface is very uneven and low friction. Initially the team wanted to create a rocker bogie suspension system, this system is the standard for lunar rovers in industry because of its unique traction capabilities. However, the rocker bogie system proved to be too complex, so a springless fixed frame was chosen instead. A springless four-wheel suspension system with individual 360° steering was chosen by the drivetrain team to maximize the maneuverability of the rover. A springless suspension is less likely to fail due to tilt. A four-wheel frame also minimizes the complexity of the system and evenly distributes weight among the four points of contact. These features make this frame system a viable solution for the design problem posed by the Pathbuilder project.

The rover is going to travel under high loads, and the torque required to move the weight of the rover limits the speed to cm/s regardless of suspension type. Preliminary analysis was done on the frame prior to manufacturing to verify the frame could withstand the static load of the rover weight. The analysis was performed by simulating a 100kg mass on the middle beam of the frame and fixing the bolt holes on each side of the frame. The results verified that the design would withstand the expected loadings.

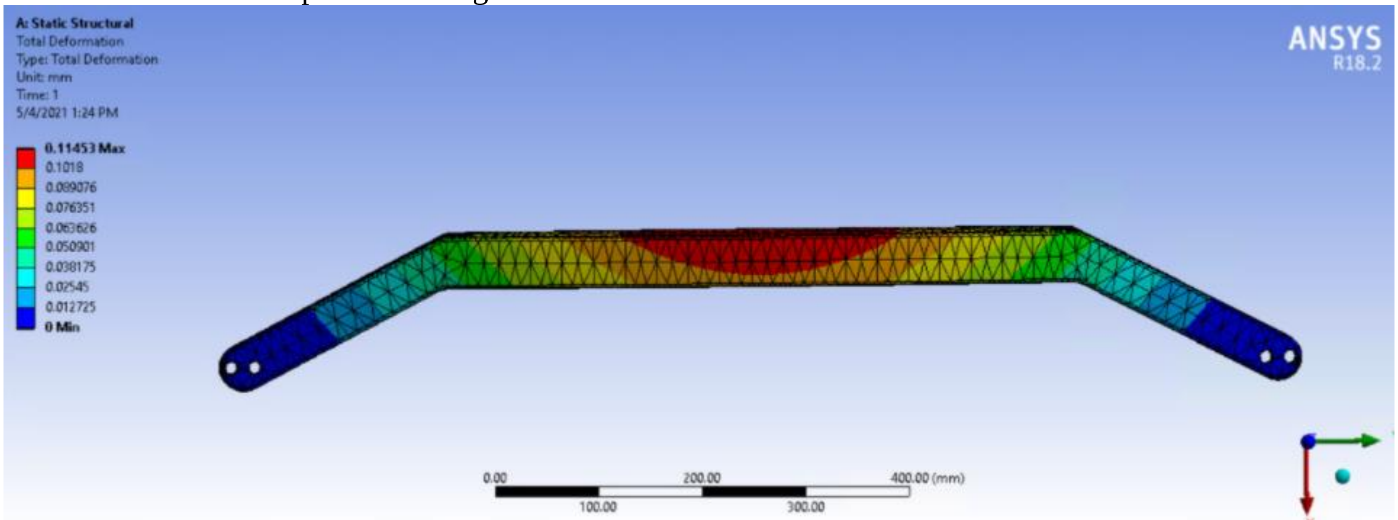


Figure 35: Deformation Analysis of the Frame

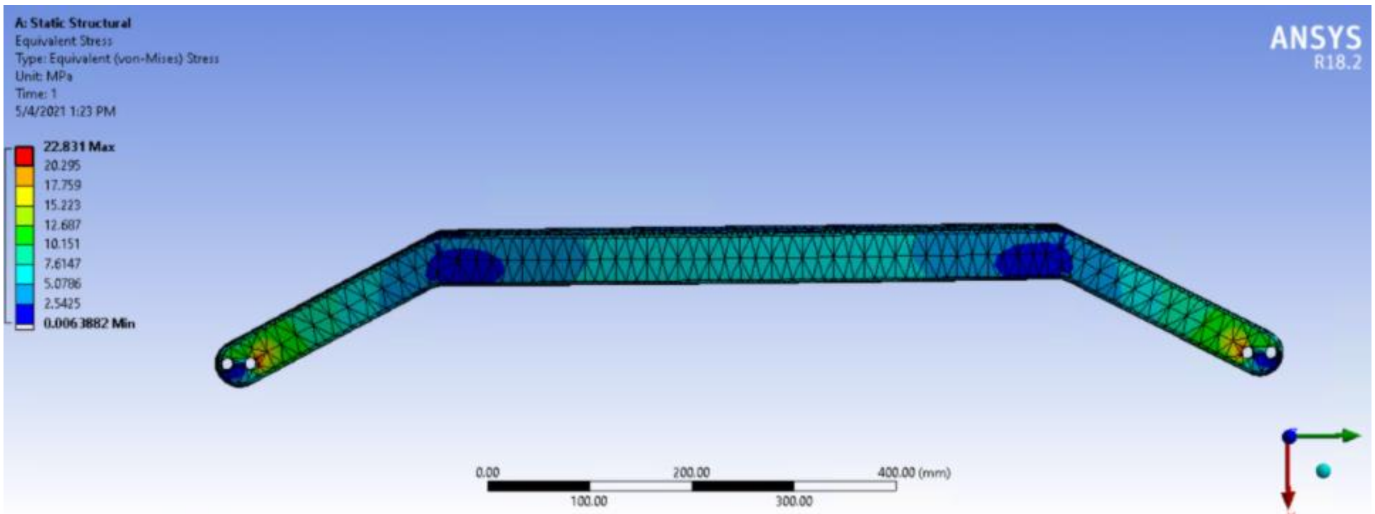


Figure 36: Max Stress Analysis of the Frame

The controlled variables in material selection are density and cost. Square aluminum tubing was selected as the frame material. This will minimize density of the frame, while maintaining a reasonable tensile and compression strength. Aluminum tubing is very machinable, and the welding and machining will be done on campus rather than being outsourced. Each side will be composed of three pieces welded together at an angle.

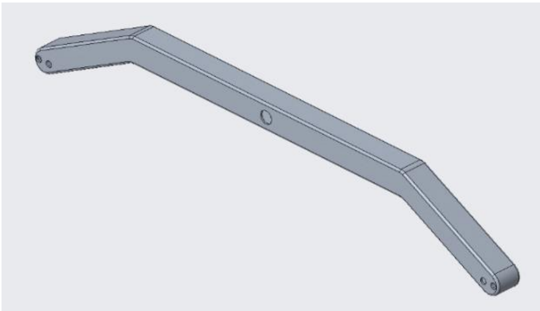



Figure 37: CAD Model of Right Frame Assembly **Figure 38:** Manufactured Right Frame Assembly

Drivetrain Frame Manufacturing:

To manufacture the frame rails to create a uniform mounting application for all other assemblies, we started with 8’ of 2”x2”x1/4” aluminum 6061 tubing, cutting to the desired lengths as per the design, which were 4-2 ½", 4-3 ½", and 2-36" pieces. Once each went through the cutting process, he used a quick square to mark the angles needed to form the correct bend, each of the 2 ½" pieces were cut at this angle, as well as the two main beams at 36”. After the cutting procedures were finished, a 4 ½" angle grinder was used along with a flap disc to buff the edges for a good mating plane to be welded together. He then created a jig using steel tubing to clamp each of the aluminum pieces to and measure in case any changes needed to be made. Once the desired form of the frame was achieved, he used a Lincoln welder equipped with ER4043 wire inside the spool gun, to weld the seams but first tacking each corner so nothing moved during the welding process as the material warmed and cooled. After welding the entire frame rail was ground to make a nice, finished appearance using the angle grinder and flap wheel again.

Steering Assembly

The steering components of the path builder rover have a significant role in the overall design, with a lot of weight on the component of this design project. The objective of the steering assembly of this rover is to produce the absolute most versatile rover possible that will handle multiple circumstances such as different types of ground. Given the specifications this rover needs to meet, it is important to give the entire rover a durable, maneuverability, reliable, and power efficient steering design. As the overall size for the rover is to be as small as possible but still be able to perform the objectives set early in the semester, we had to make a compact assembly for the steering component.

This design consists of only a few major mechanical components and an electrically powered drive system. Powering this assembly and driving the worm gear is a PG Series Gearbox motor with a 188:1 gear ratio along with a drive shaft of 10mm diameter, from this shaft we used a collar to join the driving shaft to a longer 10mm shaft to run the worm gear. With the tolerances being so precise we are using bearings to align the shaft properly which will in return align the worm gear and the driven gear. With a 40:1 gear ratio the motor will be able to turn a few revolutions for minor steering adjustments or many revolutions for major turning. The turning portion of this design is what makes it unique along with the overall design. With the huge gear reduction, it will take minimal torque to turn the driven gear which will turn the entire drivetrain assembly. As you may know the less work a system has to put out, the less power consumption it has. With less power consumption the design will remain cool while in use and save a significant amount of energy by doing this as well.

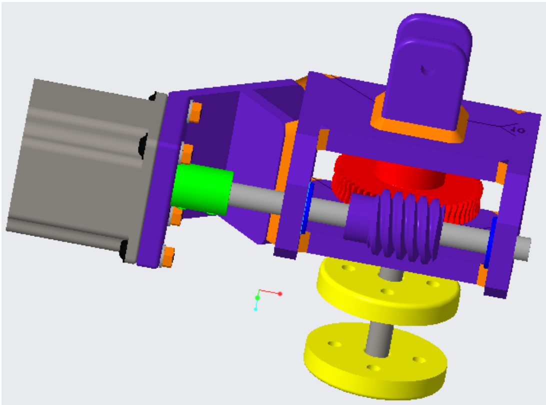


Figure 39: Steering Assembly Front Iso-view

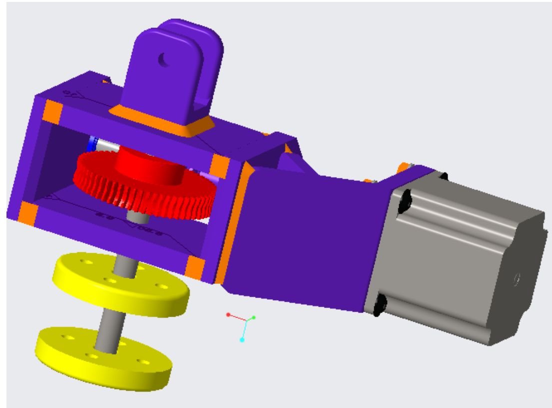


Figure 40: Steering Assembly Rear Iso-view

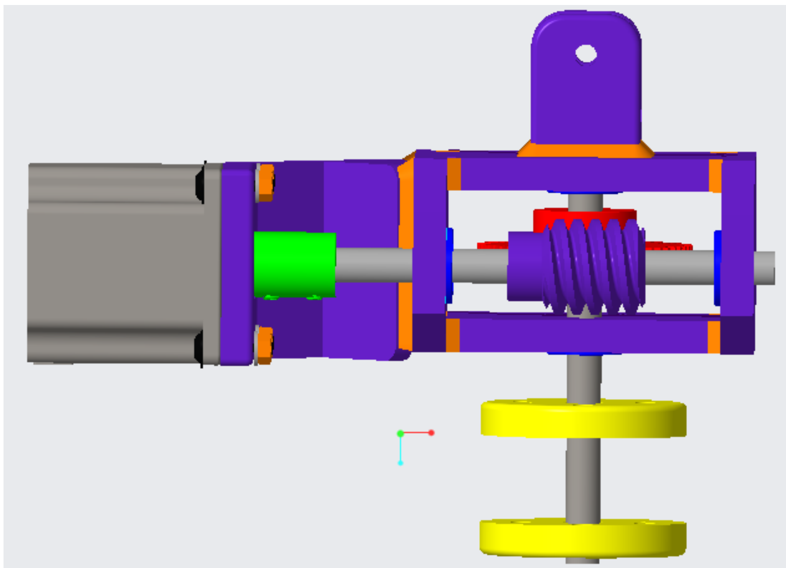


Figure 41: Steering Assembly Front View

Figure 42: To manufacture the mounting bracket to accept the PG Gearbox motor, we used 3" x ¼" 6061 aluminum angle, this saved time and money rather than bending flat strap which would add additional fabrication costs plus the material costs. The revised mount viewed in Figure 3.4.8

Figure 43: The top rod mount, using 6061 aluminum of 3/8in-2 ½in strap. Drilling procedures will take place first, followed by welding processes. It is much cheaper to make this part than it would be to machine one solid block of aluminum down to this structure. Instead of machining the round part on the bottom portion of the block, we left the main housing using Figure 3.4.7 on top only partially bored, this allowed for the top mounts to be directly welded on top as just flat strap with two holes as seen in Figure 3.4.9

Figure 44, 45: The top and side plates will be creating using the same processes so they share one description as follows, using ½" and 1" 6061 aluminum the pieces will be cut out as per desired measurements and then we will perform turning and milling operations to achieve the best tolerable hole size and surface finish.

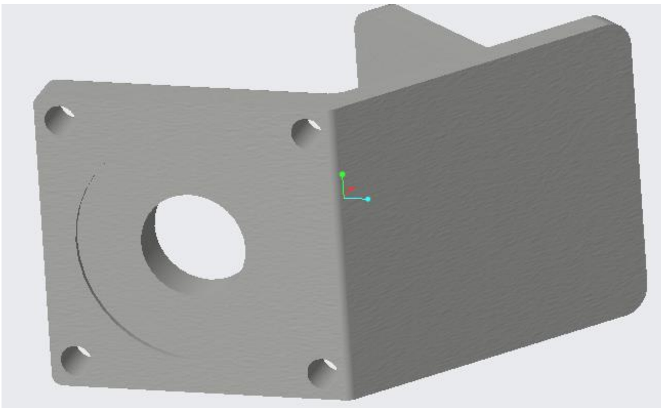


Figure 42: Steering Stepper Motor Mount Bracket

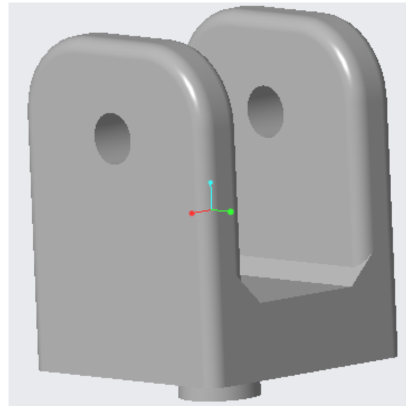


Figure 43: Steering Top Rod Mount

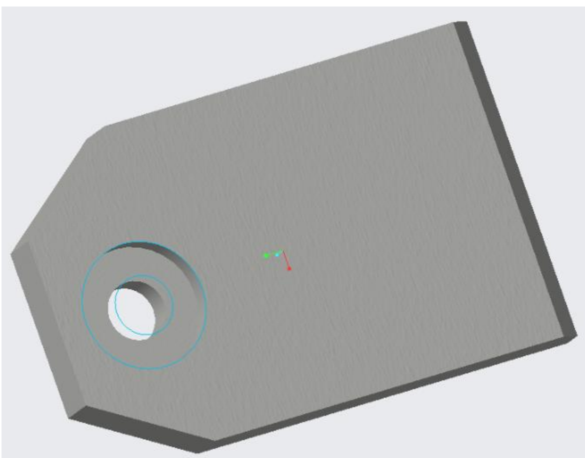


Figure 44: Steering Side Plates

Figure 45: Steering Top and Bottom Plate

Figure 46: Manufactured Motor Mount

Figure 47: Manufactured Top Mount

Steering Assembly Manufacturing:

The process to manufacture the steering assemblies, each part was broken down into distinct machining processes to achieve the most efficient way of manufacturing the entire assembly. The defined parts were broken down into sub-assemblies, this makes it easier to understand how each sub-assembly is created, the main sub-assemblies are as follows: Housing, Motor Mount, Driveshaft, Driven-Shaft, and Gears.

Housing:

Housing was created by first rough cutting, both ½" and 1” flat stock to 4 ¼", once this was done, we ground each weldment to have an angle where we were going to be welding, this will result in deeper penetration during the welding process. After that we clamped the plates around a piece of 2” x 4” rectangular steel tubing, the creating a box feature that consisted of 2- 1" x 4” aluminum plates on top and bottom of the tubing, and 2- ½" x 4” plates on each side. By clamping the plates, we restricted any movement that may have taken place during the welding process. Next, the pieces were welded using a lincoln welder equipped with ER4043 wire inside the spool gun. Once the welding process was finished all corresponding welds were ground flat, in rough preparation to surfacing the datums. Next each block was placed into the turning lathe using, a four-jaw chuck, the centering tool was used to hold the block centered while each jaw was tightened down upon the block. After the block was secured, the cutting tool was used to face each top and bottom plate, so they are perfectly parallel. After the last surface was faced off the block would remain in the chuck until the vertical hole was bored as per the design, prior to the boring process a 1 ¼" drill bit was used to get rid of some of the material. Using the boring bar multiple rough cuts were taken before taking the final finish cut to achieve maximum surface finish. At this point the turning process was completed, to bore the horizontal hole an end mill was used with an initial drilling procedure to get a starting point then finished with the end-mill bit.

Motor Mount:

Motor mount was made out of 3” x 3” x ¼" aluminum angle cut to 4 - 3" pieces, this was drilled using the dimensions given by motor drawings, once the holes were drilled, the piece was held up and clamped, then a formed piece of light steel was bent at 90 degrees to create a bolting flange to attach the aluminum angle to the housing which was bolted using ¼" grade 5 hex bolts and nuts.

Driveshaft:

The main drive shaft started out as ½" cold-rolled mild steel. First, 4 - 10" pieces were cut, this allowed for 8” of machinable shaft while having it placed in the turning lathe three jaw chuck. Next, the shaft was inserted into the chuck with only about 1 ½" sticking out, this was done on purpose to center drill the rod so the centering tool can be used to hold the none supported end of the shaft during the turning operations. Then before moving the shaft, a cutting tool was used to turn the shaft down to a diameter of 10 mm and only a depth of 8 mm, this created a step for the first bearing. After flipping and setting the shaft such that only a couple inches are in the chuck and the rest being centered at the end by the centering tool. The rest of the shaft was turned down to a diameter of 10 mm.

Driven-Shaft:

The driven shaft was machined out of ¾" cold-rolled mild steel. A step was created using the turning lathe by inserting 2 ½" of the shaft into the chuck. Then the cutting tool was used with the lathe set to a speed of 724 rpm, to cut down the rest of the shaft to a diameter of 10 mm. Lastly a 4” piece of ¾" rod was drilled out to 10 mm then reamed to create a slip-fit collar to go over the existing 10 mm rod after the gear was placed.

Gears:

Both gears were bored out to 10 mm and reamed to make them slide smoothly over the shafts, lastly both gears were drilled with a small 1/8” hole to press roll pins into to minimize slippage between the gear and shaft.

Wheel Support Structure

The goal of the wheel support structure was to attach the drive hub and wheel to the steering sub-assembly and support the weight of the rover. The part also needed to have a slim profile to allow for maximum clearance under the rover for the rover excavation features. The wheel could only be supported on one side through the inner hub, forcing the wheel support to be a cantilever design. The shaft coming out of the steering module also needs to be positioned in the center of the wheel to reduce the amount of wheel scrub.

Design

The initial design was created by making the most minimal design needed to attach the inner hub to the steering system with the steering shaft being positioned in the direct middle of the wheel to reduce wheel scrub and maximize the efficiency of the steering system. The design was chosen to be made from steel sheet metal and welded together. The decision to use sheet metal was made because the complex geometry of the part would not be very easy to machine with a conventional mill. Steel was chosen as it is much easier to work with when using a laser cutting machine and then bending material. The initial design was then created in CAD software and then an FEA analysis was performed using ANSYS Workbench.

Weight of Rev 1 2.41lbs, weight of rev 2 2.71lbs.

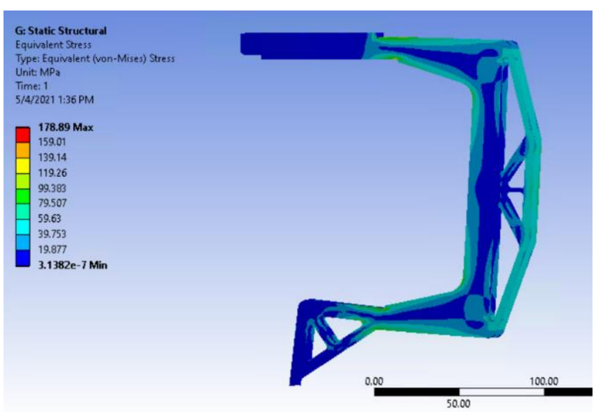


Figure 48: Support Structure Rev10 Max Stress

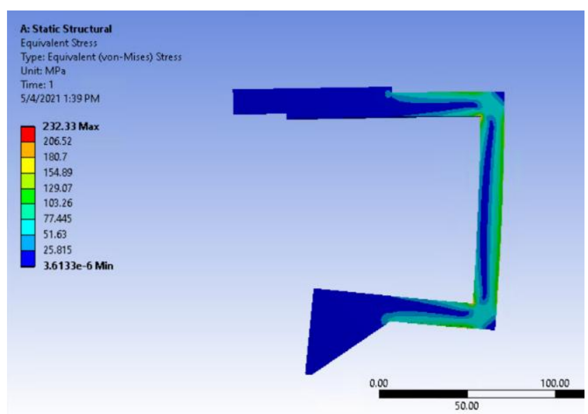
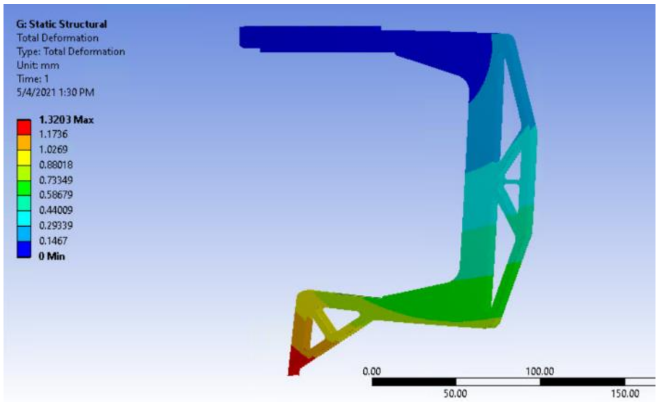


Figure 49: Support Structure Rev1 Max Stress



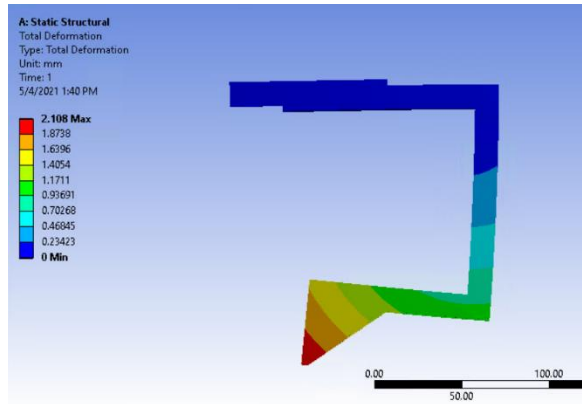
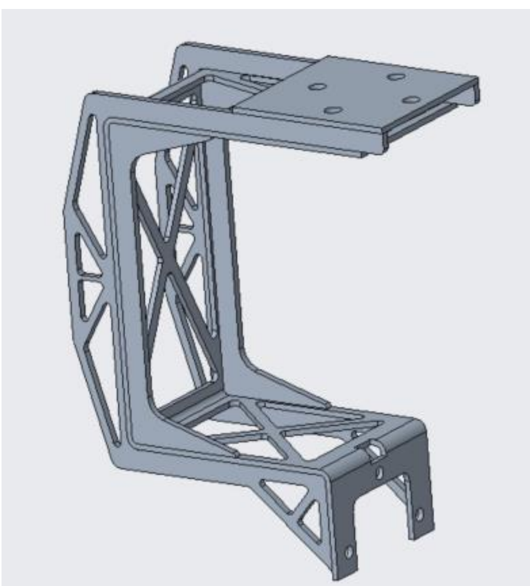


Figure 50: Support Structure Rev10 Max Stress **Figure 51:** Support Structure Rev1 Max Stress

After running many analyses using ANSYS and revising the CAD model the final geometry was chosen after 10 revisions. When analyzing the results of the FEA and determining what to do with the design, material was chosen to be removed from areas of low stress and material was added to areas of high stress. Sharp corners were also removed and replaced with large radii to prevent stress concentrations. The final design design featured many triangular perforations to maximize stiffness. Analysis of the final revision found a max stress of 178MPA when compared to the initial version which had a max stress of 232MPA. The final revision had a max deformation of 1.3mm compared to the original which had a max deformation of 2.1mm. The final version of the wheel support had a mass of 1.22kg while the original part had a mass of 1.09 kg. The increase of mass was due to the addition of two pieces of sheet metal in the inner bend of the part. Although the final part saw an increase in mass, the strength to weight ratio was increase and the overall deformation was almost cut in half. No issues with the part were found when attaching to the rover and while supporting the weight of the rover.



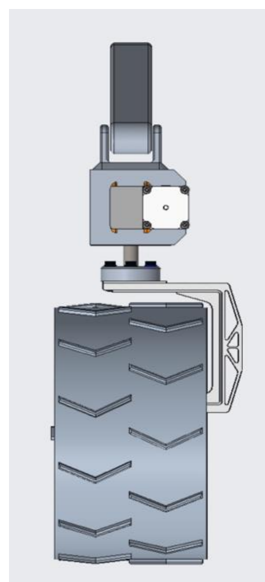


Figure 52: Wheel Support **Figure 53:** Wheel Support Structure Assembly

Laboratory Test Plans and Results

After initial assembly of the steering and powertrain subassemblies they were taken to the Electrical Engineering lab to be connected to power supplies and test the assemblies. Initial testing of the gearbox without the wheel attached resulted in a free-spin current of roughly 0.5A for all four gearboxes. Once all gearboxes were tested without issues, a wheel was attached to the gearbox to test the free-spin current. With a wheel attached the free-spin current exceeded the current supply of the power supply in use indicating there was a problem with the way the wheel was attached to the gearbox. After inspection, an issue was found where the face of the gearbox was rubbing on the face of the wheel creating unintended friction. To resolve this issue 1.5mm spacers were made using a 3-D printer and mounted between the wheel and gearbox as shown in Figure 54. After testing with the wheel spacers, all gearboxes were tested with wheels and found to have a free-spin current draw of 1-1.5A.

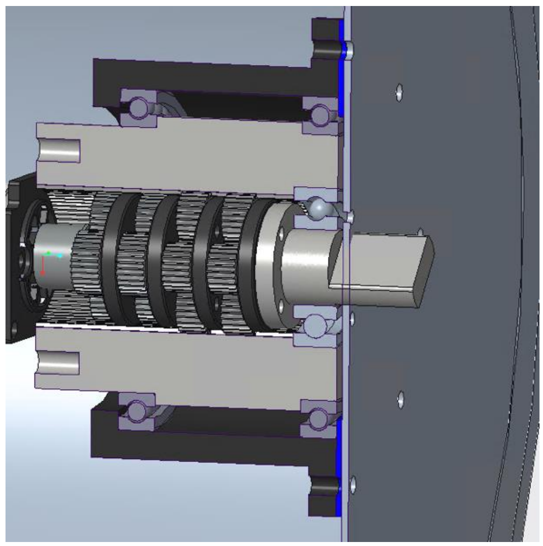


Figure 54: Assembly of Gearbox and Wheel with Wheel Spacer (blue)

Initial testing of the steering housing after manufacturing was done with a drill attached to the worm gear shaft and was successful. The steering assembly was then taken into the lab to test the steering assembly with the stepper motors attached. Initial testing with the stepper motors was unsuccessful as the stepper motors were not able to provide enough torque to turn the worm gear shaft. It was then determined that the stepper motors would not be suitable to power the steering assembly. While in the lab, the stepper motor was then replaced with a DC motor with a 188:1 gear reduction. Initial testing of the DC motor with the external gear reduction was successful in turning the wheel when the wheel was not in contact with the ground. The steering assembly was then attached to the rover and tested while supporting the weight of the rover. The test of the steering assembly with the DC motor and external gear reduction was proven to be successful by turning the wheel while supporting the weight of the rover.

Excavation Team

Detailed Design Documentation

Rock Breaker

While detailed design analysis had been performed on the rock breaker first semester, there was not enough information to justify its existence within the Pathbuilder concept. With the advice of NASA mentors, the rock breaker subsystem has been dropped from the design.

Excavator

A few key changes were made to the design of the excavating conveyer between initial conceptualization and final product. These changes were thoroughly thought over as they did bring many large changes to the functionality and design of our components. These changes where problems that we thought would occur as other subsystems of the rover went through redesign as well. Some changes were brought about from advice from our sponsors at NASA as well as feedback from the mentors after our first semester presentation.

The chain path was modified to move the bucket drop-off point to the middle of the hopper opening while keeping a near vertical angle for the body of the conveyer. This required a convex corner to be added to the chain path, and the bucket design needed to be changed to accommodate this. MATLAB code was used to determine the total length of the chain that would be required to run the rover with minimal slipping while not being too stretched out when the conveyor is in the stowed position. We were able to get the conveyor to this point over the hopper by adding a mounting tower over the hopper opening. A shaft was run through this tower, and it was also decided that this is where the motor would be mounted to drive the shafts. This position for the motor was chosen because it is on the end of the conveyor, and it is in close proximity to the electronics enclosure, making the wiring cleaner and so wires would not interfere with any components of the rover.

The bucket saw a near complete redesign considering the new requirements from the chain path change as well as advice taken from advisors at the semester 1 final presentation. The new buckets would be made from sheet metal, with significant weight reduction over the first semester design changes. Upon consultation with Kava Fabrication (the supplier, the material for these new buckets was changed from aluminum to steel to negate the need for tig welding and bring the cost to within budget. By switching from aluminum to steel, we were able to make the buckets out of a lower gauge steel than we would have made it out of aluminum. This is because of how much stronger steel is and aluminum. We opted for a 12 Gauge sheet metal for workability as well as a guarantee that the buckets would be sufficiently strong enough to withstand the abrasive material it is digging through.

It was decided that the Excavator would use a chain tensioner that would utilize chain slack between the stowed and deployed positions to extend the digging area of the buckets and allow the buckets to have a reduced angle of attack.

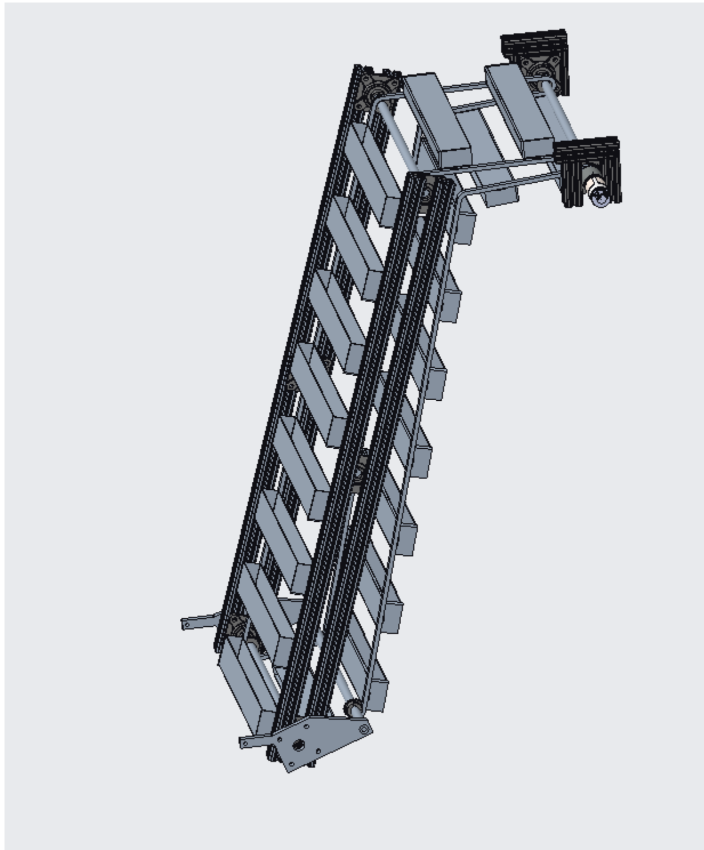


Figure 55: Excavator CAD

The dimensions of the conveyer and tensioner were parametrized using MATLAB R2017a, and the length of the conveyer and chain tensioner were decided based on the following parameters: Conveyer mounting height, deployment angle, stowed angle, digging angle of attack, and digging depth. Parameterization of the dimensions of the conveyer allowed the design to be very easily changed to match any new design changes brought forward from the other sub teams. Parametrization also allowed the final chain length and other dimensions to be instantly changed based on any variations between the design and the dimensions of the final product, which made proper bucket spacing significantly easier to accomplish. Upon inspection of the final dimensions of the Structure and drivetrain finished subassemblies, the tensioner length was set at 143mm. The chain tensioner significantly complicated the geometry of conveyer and introduced several codependent geometries, for this reason, parametrization was a requirement to achieve a functional result.

The Component fabrication and frame assembly was finished in Dolve hall, while full assembly and integration to the rover occurred in the electrical engineering building.

Compaction Roller

The compaction roller utilizes an H-frame design. This allows the frame to be structurally sound, while still offering geometry for mounting the drum and interfacing the roller to the rover. The roller assembly can be seen below in Figure 56: Compaction Roller Assembly in CAD

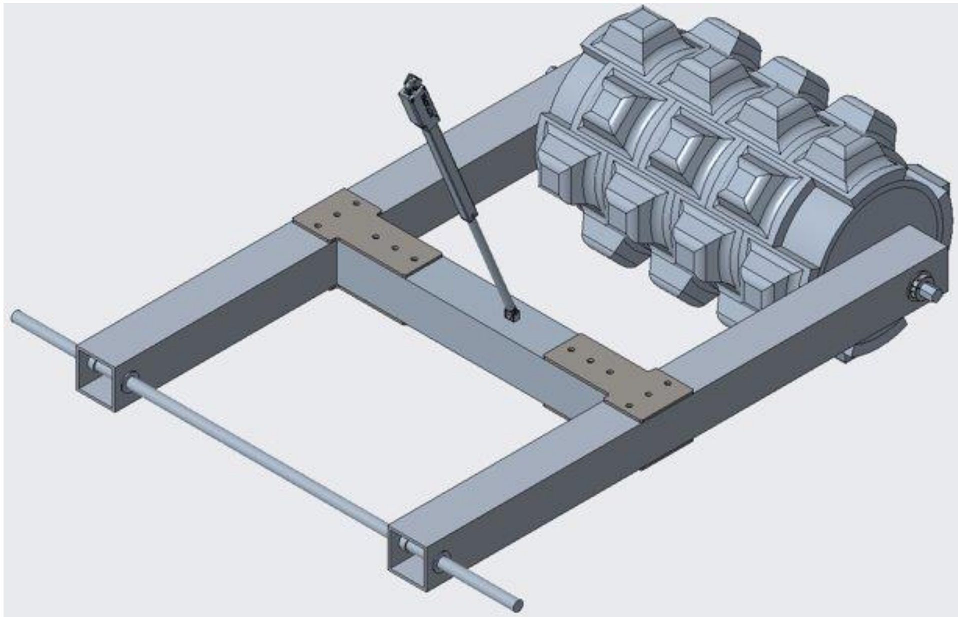


Figure 56: Compaction Roller Assembly in CAD

The “sheepsfeet” protrusions on the drum allow for higher compaction pressure than a typical smooth faced drum. Since pressure is force divided by area, a lower cross-sectional area yields a higher compaction pressure. The drum rotates using a live axle setup powered by a bushed DC motor. A high gear ratio is required for the roller, as the motor controller is only capable of outputting a maximum of 3 amperes. The gear ratio powering the drum is 1375:1. By calculating the radial velocity of the drum with this gear ratio and the expected rotational velocity of the motor output shaft, the tangential velocity of the drum can be calculated. The gear ratio of the roller and the outside diameter including the sheepsfeet matches the velocity of the rover drivetrain system.

The compaction roller is comprised of aluminum square tubing, aluminum circular pipe, and aluminum flat bar. The fabrication of the roller occurred in Dolve Hall over the course of two weeks. To epoxy the sheepsfeet to the drum, both surfaces were sanded with low grit sandpaper to improve grip. The drum is supported by roller bearings for longevity and ability to absorb radial loads.

Laboratory Test Plans and Results

Sheep’s Foot Roller

The sheep's-foot roller is planned to be tested using the gravel pit at the NDSU Innovation studio using the whole Pathfinder rover. The gravel pit will need to have an area dug up to reduce the compaction caused by bobcat testing as well as other vehicles and personal moving across the surface. Once the surface has been setup to gather compaction data, control and test data will be gathered using a surface penetrometer to measure surface compaction level. The hopper would be filled with a measured weight gravel and the surface compaction would be plotted against the weight in the hopper of the conveyer. The effectiveness of a passive, mass driven system such as the sheep's foot roller will be evaluated based on the level of compaction measured through this methodology and could be used to judge whether it would be a fitting system for surface compaction on the lunar surface.

Excavation Conveyer

Testing of the excavation conveyer will be conducted by monitoring the power consumption to move a specific amount of regolith. Through these metrics in combination with the power requirements of the other subsystems, an effective digging volume unit of energy could be calculated. This information could be of significant use for future endeavors to the moon's surface and as an indicator of the efficiency of Pathbuilder's excavation system as a concept.

The level of dust kickup on the rover will need to be evaluated as it pertains to the hinderance inflicted on other subsystems. The rover will need to be cleared of all dust on the solar panel, drivetrain, and electrical components before the excavating conveyer is tested. After testing, each subsystem will need to be thoroughly checked for dust and the interference of the dust buildup on major components will need to be thoroughly analyzed. The Pathbuilder concept requires the rover to function for long periods of time with little to no maintenance, and dust buildup on vital systems needs to be critically inspected to assess the viability of the conveyer as an excavation device. It should be mentioned that the test environment will not be able to accurately replicate the behavior of dust particle on the lunar surface where the particles wouldn't lose momentum from atmospheric resistance, and the applicability of this particular test will need to be evaluated by NASA employees or future students who are more familiar with low gravity, vacuum particle mechanics.

Electrical Team

Requirements

What does it do? The Path builder Rover is an earth prototype designed to scrape and flatten regolith-like materials. The rover will be controlled remotely and charge via its onboard solar panel. The rover will lift regolith using a conveyor belt and compact the surface with a heavy roller.

Input Voltage: The rovers primary power source will be a 12V, 105Ah Li-Iron battery. The battery will then power both 12V and 5V systems.

Current Draw: The operating current is hard to quantify, as it will vary with different loads. If all motors were running at the same time, the max current draw would be 38A. This operating condition is unlikely, under normal use we anticipate 30A, and ~1A during standby.

Environmental Considerations: The rover itself is primarily self-sustaining, as it relies on solar energy. With that, the rover's purpose is to excavate and flatten. Operating this rover has a considerable risk of damaging the moons environment. Additionally, the process of getting this rover onto the moon will use a significant amount of fuel. The decoupling procedures with rockets and boosters will also introduce unwanted debris into orbit. Unwanted organisms and bacteria may also be introduced to the moon inadvertently.

Global Considerations: Pathbuilder is designed to be remote controlled. Work done using Pathbuilder allows compaction to be done without endangering any persons. With a remote control, this will pave the way for individuals to keep themselves out of harm's way when operating machinery that could otherwise would require direct, hands-on human guidance.

Economic Considerations: Pathbuilder is designed to bulldoze and flatten the surface of a lunar surface. Flattening the lunar surface allows for the construction of roads and buildings that will help to further our lunar expeditions. This flattened regolith will also provide better dust mitigation allowing us to minimize the amount of regolith that is being tossed around from the equipment, which will hopefully reduce damages and regolith collection. This will allow humanity to go further into our solar system and allow for a cheaper and more efficient way to traverse space.

Societal Considerations: This project works towards providing one of the many aspects that are required for greater space travel. This makes one step more towards the idea of a delocalized society inhabiting an extraterrestrial body. Such action comes with the risks and troubles an extended population may face.

Visual/Auditory Alerts: For this prototype there will be minimal auditory and visual alerts. The onboard solar charger will indicate the battery voltage and load/charging currents. Additionally, the motor controllers will also have small leds on them, to indicate if a motor is spinning. There are currently no permanent residents of the moon that could be disturbed by any alerts. Auditory alerts have also been disregarded, as there would be no sound in the vacuum of space.

From the control panel, we can send and receive data. Through this data, we can get a visual representation of our sensor's readings. The control panel also has the potential to provide with warnings and errors in operation as the controllers identify them.

Figure 57, DC motor and gears to drive hopper conveyor.

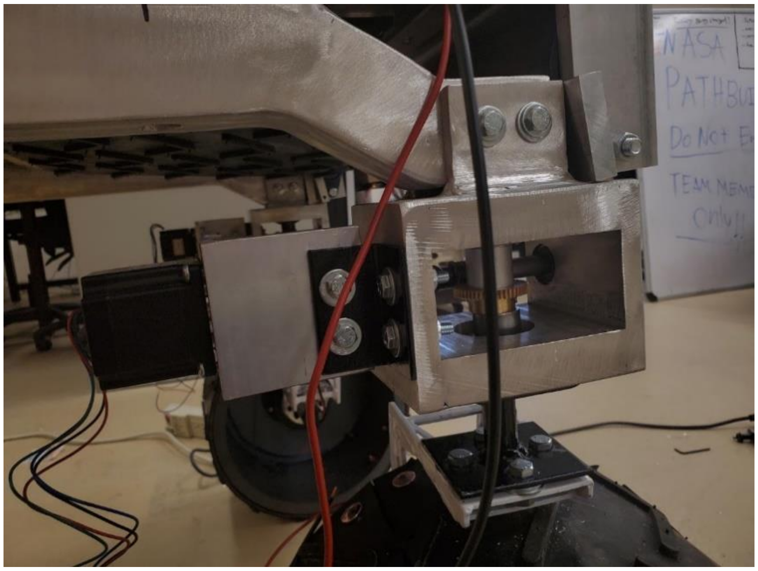


Figure 58, Stepper Motor and gearing to rotate wheels

Figure 59, Electronics Enclosure before mounting

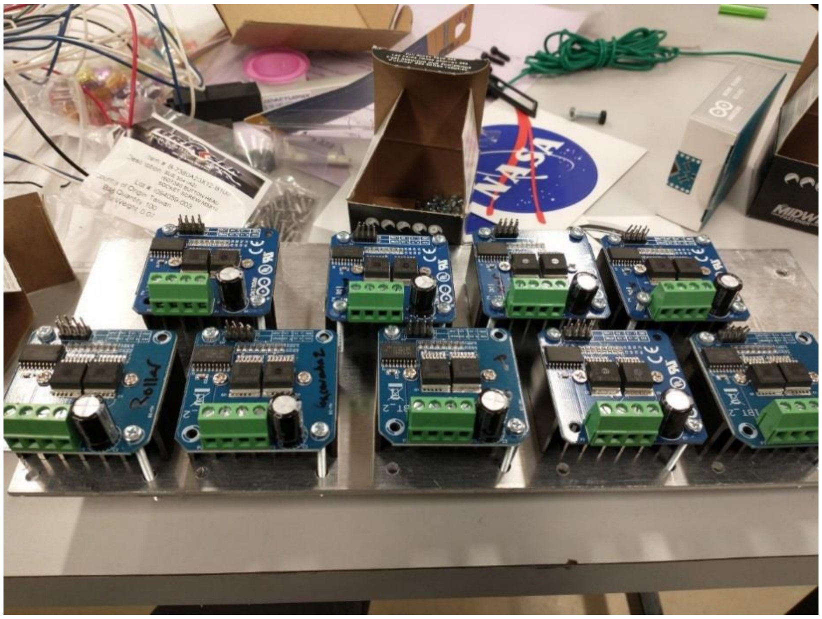


Figure 60, Mounting BTS motor controllers to plate

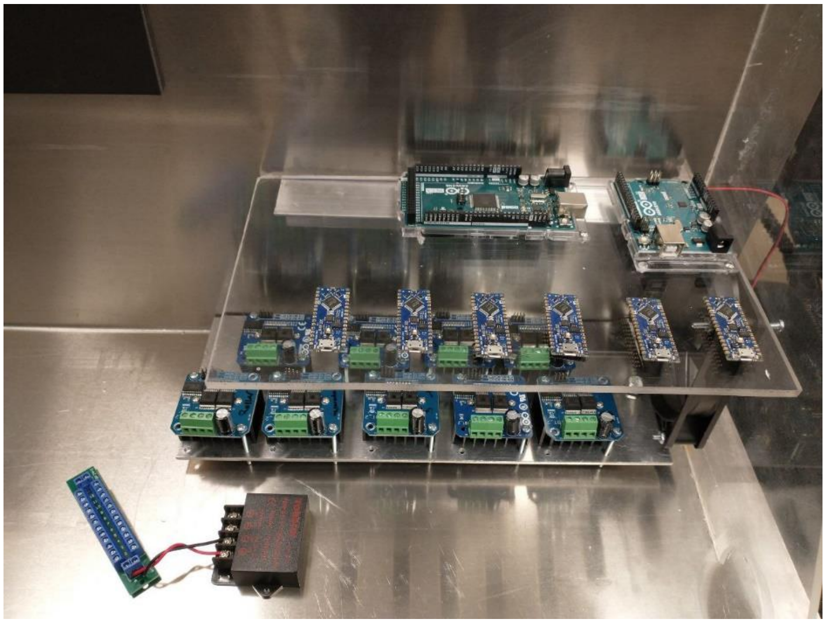


Figure 61, Arduinos mounted above Motor Controllers

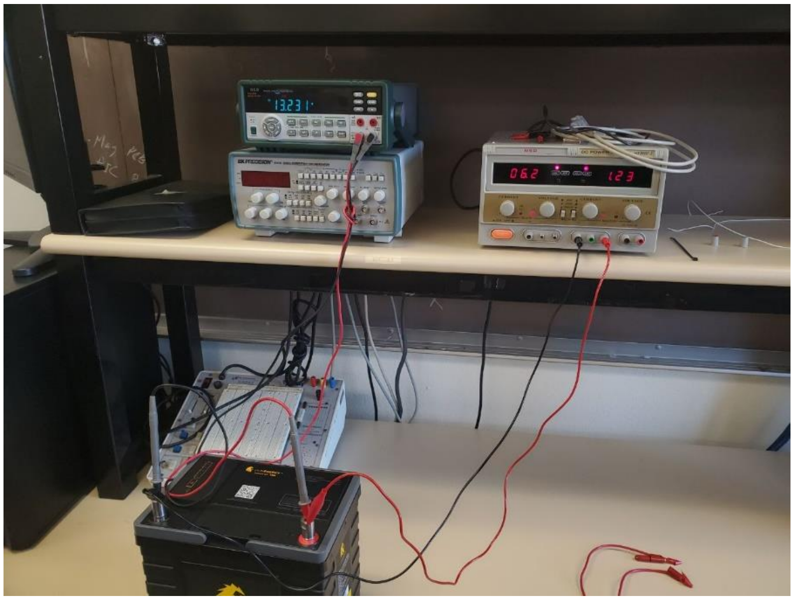


Figure 62, UT1300 charging.

Operations Manual

System Overview

The Pathbuilder rover is an earth prototype designed to demonstrate excavation technologies that could be employed on the moon. The rover has a solar panel capable of rotating and tilting, a conveyor belt to intake regolith, a conveyor belt to dispel regolith, a compaction roller, and drive system. As of now, the rover is not fully functional, only the basic functions have been achieved such as driving forward and backwards.

The Rover is equipped with 2 batteries. A high power 12V, 105Ah Li-Fe battery is used to power the motors and subsystems. A smaller 5V battery is used to power the Arduinos. This enables troubleshooting to be done with the microcontrollers without 12V and ensures the rover can still communicate if something goes wrong on the 12V system.

The rover is designed to be controlled remotely and is capable of 2-way RF communication up to 50 feet. An external PC is needed along with an Arduino and RF hardware to communicate with the rover. The rover is also capable of outputting a video feed using FPV drone cameras. To access this footage and FPV receiver also needs to be connected to the PC. Through command line instructions, the user can request data from the rover or instruct a subsystem to execute a function. The RF signal is received by an Arduino Mega on the rover and then sent to the appropriate subsystem using I2C.

Battery Safety

Before any work can be done with the rover or its battery, a battery safety training must be completed. This rover uses a high-power battery and has the potential to cause serious harm. In response to a short circuit incident with the UT-1300 battery, a Standard Operating Procedure for high power batteries was created by the team. Be sure that you have read and fully understand the operating procedure.

Setup

Before using the Pathbuilder rover, the following equipment and setup is needed.

- A PC with the Arduino IDE, and Open Broadcaster Software (or other software capable of viewing two USB camera inputs).
- 1x USB to Printer Cable
- 2x USB-C to USB-Micro
- Arduino Uno with nrf24l01+
- FPV Receiver

Pathbuilder Rover

The user can begin communication with the rover if the Arduinos on the rover are powered with 5V. The battery does not need to be connected unless the subsystems are being used.

To use the Pathbuilder rover and all its subsystems, the UT-1300 battery needs to be installed. Ensure that the solar panel charge controller is configured correctly (see Power Systems), fuses are installed, and all connections are secure. The 12V from the battery can then be enabled by turning the master switch atop the robot to ON.

System Architecture

The Software Architecture of the Pathbuilder Rover follows a "Master, Slave" approach. This approach allows for top-down control of the rover, having each system split up both physically and digitally. This system is connected via a I2C nervous system that makes sending and receiving data simple and cheap. Commands and data can be sent to the relevant subsystem using the I2C bus. The master can also receive data from subsystems if requested.

The hardware part of the rover primarily consists of Arduinos, Motor Controllers, Power distribution, RF modules, Sensors, and charge controllers. The rover is powered with a 12V battery which is split into 12V and 5V voltage rails. This power is then delivered to motors using motor controllers interfaced with Arduinos. The hardware involved in each subsystem can be found in the subsystem section and attached schematics.

Communication Protocol

Pathbuilder uses a variety of communication protocols. Due to the nature of the systems structure, these protocols need to send and receive data, as well as relay this data to a host PC.

For our wireless communications to and from the host PC/Master Arduino, we used a "nrf24l01+" chip. This provided us with a low power, easy to maintain and expand upon base, that we created a command system out of.

For communication on Pathbuilder, from Arduino to Arduino, we used I2C. This allowed our team to chain Arduinos such that sending and receiving data was quick, reliable, and low cost. Existing Arduino libraries were used for the nrf24l01+ and I2C communications.

Sending Commands

Sending commands is done from the host PC to the master Arduino over an Arduino Uno. This Arduino is connected via USB to the Host PC and is controlled via COM port. A command can be sent through COM communication to the Arduino UNO connected to the host PC, and that command will transmit over RF to the Master Arduino Mega. This communication is done via the "nrf24l01+" chip mentioned above and is all structured in "C" code.

When a command is sent from the host PC to the Master Arduino, it is parsed by character. The first character, parsed by the Master Arduino, will specify which "sub-system" is being hailed. Once the Master Arduino determines which subsystem is needed, it will forward the rest of the command over I2C to its respective Arduino Uno.

When an Arduino Uno receives a command from the Master Arduino it will parse though the command, and determine what method needs to be activated. In some cases, this will also send data back to the Master Arduino, which will get relayed even further back to the Host PC.

Power

Pathbuilder is powered using solar energy captured with its 100W windynation solar panel. This panel is connected to a 30A windynation solar charger that will charge the 12V 105Ah lionenergy battery that is onboard. Connected to the 12V Li-Ion battery we have a 40A fuse and a 60A flyback diode for circuit protection as well as a Kohree Battery Disconnect Switch as a safety measure if we needed to turn the system off quickly.

This will then send 12V to BTS7690 half-bridge breakout boards that will control our onboard motors. It will also power two L298N boards, two MDD3A boards, and one TB6600 board. We are also using two 12V to 5V converters to send power to Arduinos and some of the boards mentioned above. Finally, we have included a battery switching module that will automatically switch to a 5V backup battery that will continue to power the onboard Arduinos when the 12V supply is cut off.

Charging

There are more ways than one to charge the battery on board. One is by utilizing the onboard windynation Solar Panel, the other is by appropriately and cautiously connecting the Lion Energy Safari UT 1300 battery to a certified car battery charger.

In order to handle the battery one must refer to the "Battery Safety" portion of this report and work with the appropriate authority to gain proper access.

Master Arduino

The primary micro that interfaces each subsystem is an Arduino Mega. This micro is responsible for all communication between the rover and operator using the nrf24l01+ module. The Mega is also responsible for sending instructions to the appropriate subsystem via the rovers I2C bus. Additionally, the Arduino Mega has sensors to monitor the battery temp, enclosure temp, battery voltage, 5V voltage and turn on/off the enclosures fan.

PC Arduino

The PC Arduino allows the user's PC to interface with the nrf24l01+ transceiver module. The Arduino communicates to the user's PC via a serial port at 9600 baud. Commands are sent to PC Arduino using the serial command line and are then transmitted to the rover using the RF module. Data sent back from the rover is then sent to the PC using the same serial port. Every command sent to the rover should have data sent back to the PC. More information is provided in the software sections.

Drivetrain Arduino

Each wheel of the rover is considered a separate subsystem controlled by an Arduino Nano. This subsystem is responsible for driving the rover forward/backward and rotating the wheel +/- 180 degrees. This action is achieved through 2 DC motors, both with built in quadrature encoders. The system is also designed to accommodate a dual potentiometer, giving the system feedback on the wheels absolute angle.

Originally, each wheel was supposed to be able to turn. Unfortunately, the motors chosen were unable to supply the needed torque. Due to time constraints, only the front wheels can be steered. The functionality is in place to steer the back wheels; however, the hardware is not.

The drivetrain subsystems can be controlled with the following designators:

System	Designator
Front Right	D1
Front Left	D2
Rear Left	D3
Rear Right	D4
All Wheels	D0

The following commands can be used to control the Drivetrain system.

Function	Command Format	Description
Stop All	D# XX 000	Stops both the drive motor and steering motor immediately.
Drive Forward, Fast	D# FF 123	Drives the drive motor at full speed for num * 100 encoder counts.
Drive Forward, Slow	D# FS 123	Drive the drive motor at half speed for num*100 encoder counts.
Drive Reverse, Fast	D# RF 123	Drives the drive motor backwards at full speed for num * 100 encoder counts.
Drive Reverse, Slow	D# RS 123	Drive the drive motor backwards at half speed for num*100 encoder counts.
Turn Wheel to Angle	D# TW 123	Turn the drive wheel to the given angle. Angle = num – 180. Ex. TW 180 means rotate to 0 deg
Read Angle	D# RA 123	Reads the dual Potentiometer and estimates the current wheel angle. Returns -180:180

The drive motor is a DC neverest Motor, am-3104b_17t with a built-in quadrature encoder. This motor is driven by a BTS790 motor controller running off 12V. The wheel has a 13-inch diameter, and the motor goes through a 1296:1 gear box. The encoder has 28 counter per motor shaft revolution. Every 36,288 counts correspond to 40.8-inches of travel.

The motor to steer the rover is a DC PG188 motor with a 188:1 gearbox and built-in encoder. There is a 40:1 gearing from the gearbox output to the wheels rotation, resulting in a 7520:1 motor to rotation ratio. The encoder counts per revolution are not called out on the datasheet and needs to be verified in the lab. This motor will also be driven by a BTS790 from the 12V bus. A dual potentiometer is intended to be attached to the wheels rotational shaft. This allows the wheels orientation to be measured.

Excavation Arduino

The intake conveyor, linear actuator, and hopper conveyor are controlled by an Arduino Uno. This system is referenced as the Excavation subsystem. This subsystem is responsible for driving the intake conveyor and monitoring limit switches for any objects that might jam. This system is also in charge of emptying the hopper by reversing the hopper conveyor. Both conveyors will be driven by DC motors.

The Excavation subsystem can be controlled with the following designator:

System	Designator
Excavation	EX

The following commands can be used to control the excavation subsystem:

Function	Command Format	Description
Stop All	EX XX 000	Stops both the conveyor belts immediately
Intake (Conveyor) Forward Counts	EX IF 123	Drive the intake conveyor to fill the hopper, runs for num*100 encoder counts at full speed.
Intake (Conveyor) Reverse, Counts	EX IR 123	Drive the intake conveyor backwards, runs for num*100 encoder counts at full speed.
Hopper (Conveyor) Forward, Counts	EX HF 123	Drive the Hopper conveyor to unload material. Runs at full speed for num*100 encoder counts.
Hopper (Conveyor) Reverse, Counts	EX HR 123	Drive the Hopper conveyor backwards. Runs for num*100 encoder counts at full speed.

Hopper Shake, Counts	EX HS 123	Drive the Hopper conveyor forward for num*100 encoder counts at full speed, then backwards for the same number of counts.
Raise Intake	EX RI 100	Retract the Hoppers Linear Actuator Num = 100 will drive it full closed, else it will run for ~0.5”
Lower Intake	EX LI 100	Lower the Hoppers Linear Actuator Num = 100 will drive it all the way down, else it will run for ~0.5”
Read Switches	EX RS ###	Reads the state of all limit switches and returns them.

Both conveyors are driven by a DC PG516 Gearmotor, with a 516:1 ratio. Each motor has a bult in quadrature encoder with 7 counts per revolution. The motors are driven by a BTS7690 Motor Controller. Linear actuators are used to lower/raise the intake conveyor from the ground. These actuators run off of 12V and are controlled using an L298N H-bridge.

Roller Arduino

The roller subsystem is responsible for raising/lowering the sheep-foot roller and driving it. This system is controlled with an Arduino Nano. The roller will be driven by a DC motor.

The Roller subsystem can be controlled with the following designator:

System	Designator
Roller	RO

The following commands can be used to control the roller subsystem:

Function	Command Format	Description
Stop All	RO XX 000	Stops both the Roller and Linear Actuator.
Drive Roller Forward, Slow	RO DS 123	Drive the Roller forward at half speed for num*100 encoder counts.
Drive Roller, Fast	RO DF 123	Drive the Roller forward at full speed for num*100 encoder counts
Reverse Roller, Slow	RO RS 123	Drives the Roller backwards at half speed for num*100 encoder counts.

Reverse Roller, Fast	RO RF 123	Drive the Roller backwards at full speed for num*100 encoder counts.
Lift Roller	RO LR 123	Lift the roller by retracting the linear actuator. If num=100 retract all the way, else retract ~0.5”
Drop Roller	RO DR 123	Lower the roller by expanding the linear actuator. If num = 100 lower all the way, else retract ~0.5”

The roller is driven with a DC neverest Motor, am-3104b_17t with a built-in quadrature encoder. This motor is driven by a BTS790 motor controller, running off 12V. The Linear actuator is a ~6” stroke and is driven from 12V and an L298N. This actuator raises and lowers the roller.

Solar Panel Arduino

The solar Panel subsystem is responsible for changing the tilt and rotation of the panel. It is also interfaced with a solenoid valve which can be opened to clean the panel with compressed air. Light sensors are also available on each corner of the panel letting the user optimize the best panel position.

System	Designator
Solar Panel	SP

The following commands can be used to control the Solar Panel subsystem:

Function	Command Format	Description
Stop All	SP XX 000	Stops both the panel from rotating and tilting.
Raise Panel	SP RP 123	Lift the panel by expanding the Linear actuator for num second or until the limit switch is hit.
Lower Panel	SP LR 123	Lower the panel by retracting the Linear actuator for num seconds or until the panel hits its limit.
Rotate Left	SP RL 123	Rotate the panel CCW to num degrees. EX num = 90, rotate CCW 90 degrees.

Rotate Right	SP RR 123	Rotate the panel CW to num degrees. Ex, num = 90, rotate CW 90 degrees.
Puff Air	SP PA 123	Excite the solenoid for 0.5 seconds. Allowing a puff of compressed air to blast over the panel.
Read Light Sensors	SP LS 123	Read the light levels for the 4 light sensors. Return the data.
Read Panel Angle	SP RA 123	Read the solar panel location from the dual potentiometer. Return the results.
Optimize Position	SP OP 123	Use the light sensor data to raise/lower and rotate the panel to find the most sunlight. Run for num iterations.

The solar panel tilt is controlled by a 12V linear actuator and is drive using an L298N motor controller. The rotation of the panel is controlled using a geared stepper motor using a TB6600 micro step controller. The solenoid is controlled using the other half of the L298N that is being used for the panel tilt. Voltage dividers made up of photoresistors are sued to get light data about the panel.

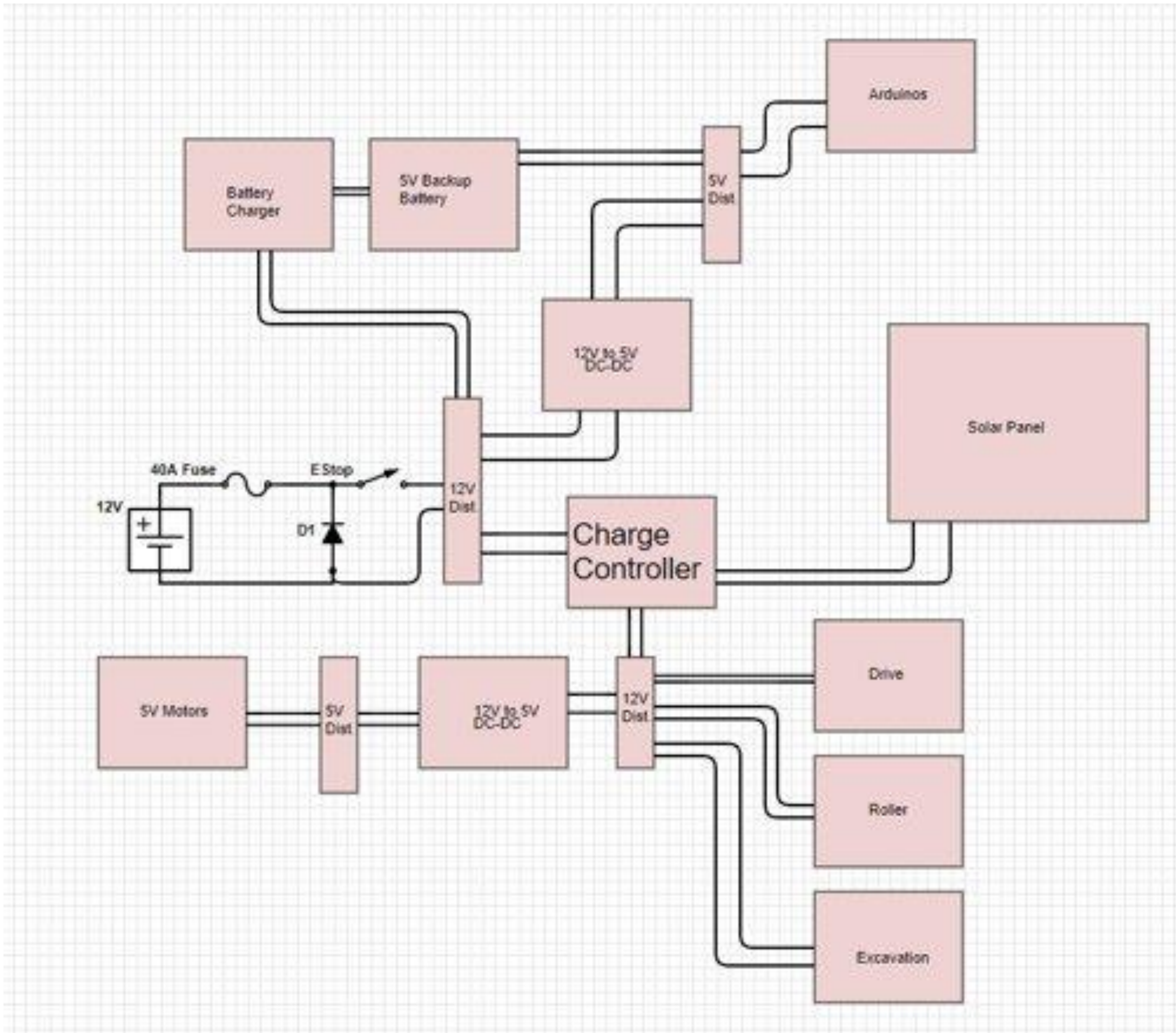
Shutdown and Storage

1. Standard shutdown procedure will be as such.
2. Verify no systems are running any functions that include any moving parts on the rover
3. Flip the emergency stop switch on top of the rover close to the solar panel.
4. Carefully disconnect and remove the battery.
5. Shut down the control PC and Arduino.

For storage, due to the nature of electronics on board, no power should be present in the system. This means no battery should be connected. Be sure to store the rover in a safe, controlled environment, away from external interruptions.

Hardware Block Diagrams

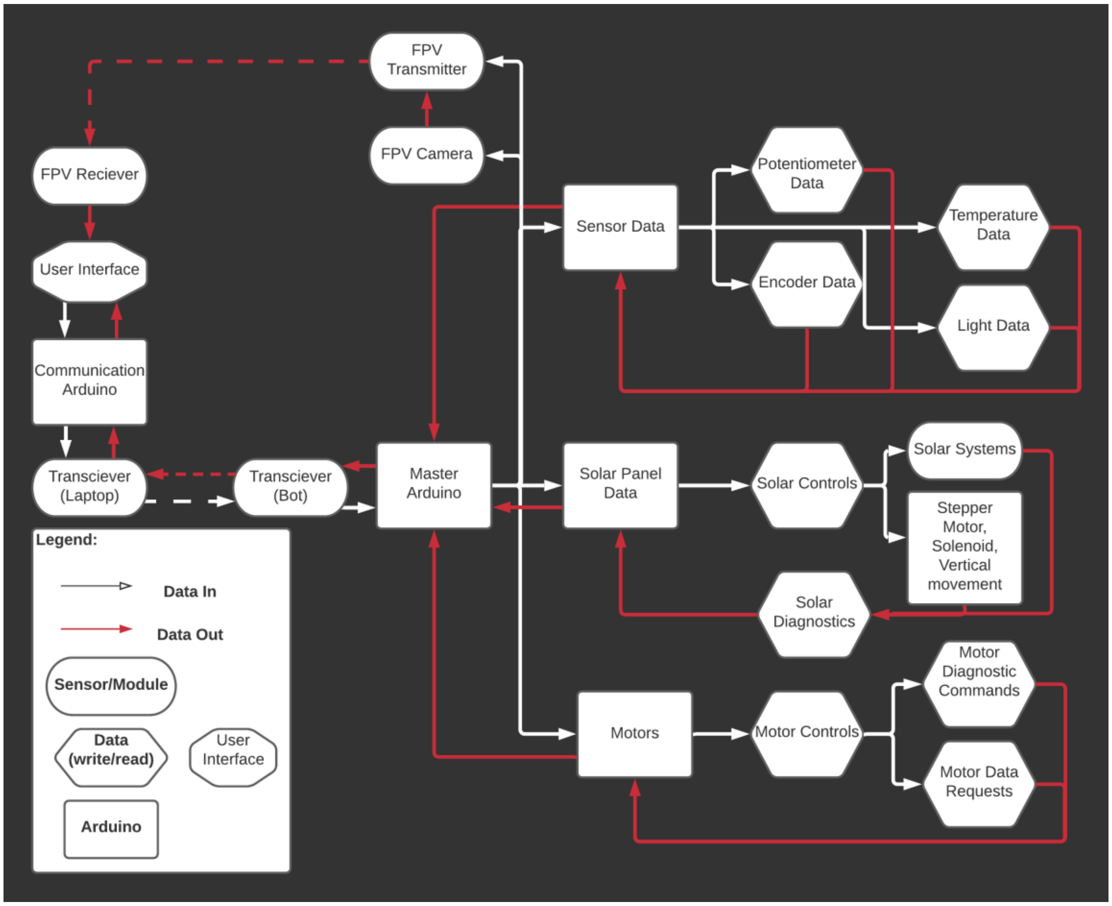
The following diagram shows the overall hardware design for Pathbuilder and its functionalities.

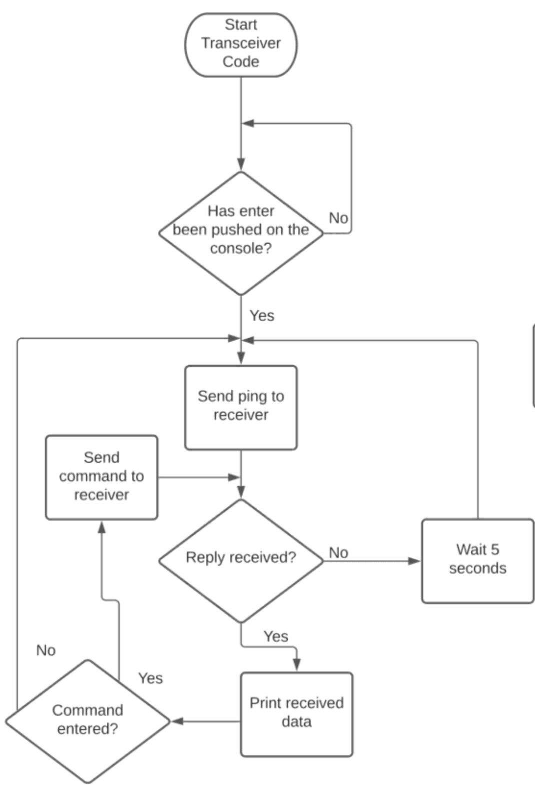


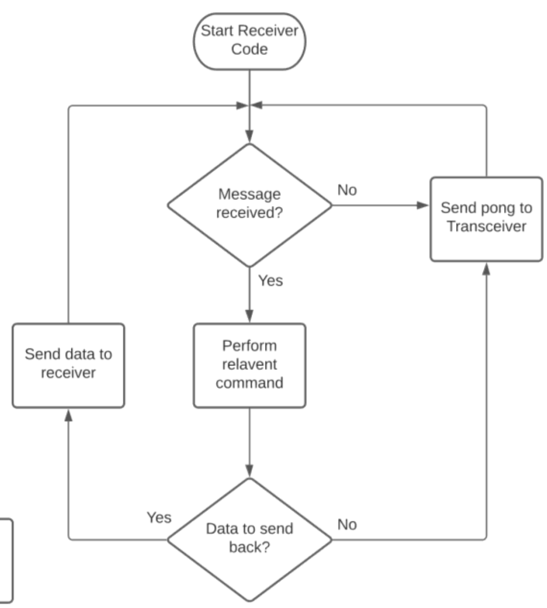
The 100W solar panel will collect solar energy from the sun and use that to charge the 12V Li-Ion battery onboard. That 12V battery will then be used to power our motors and it will also be sent to a DC/DC converter that will step the voltage down to 5V which will then be used to power our Arduinos, and a variety of breakout boards for the system.

Software Flow Charts

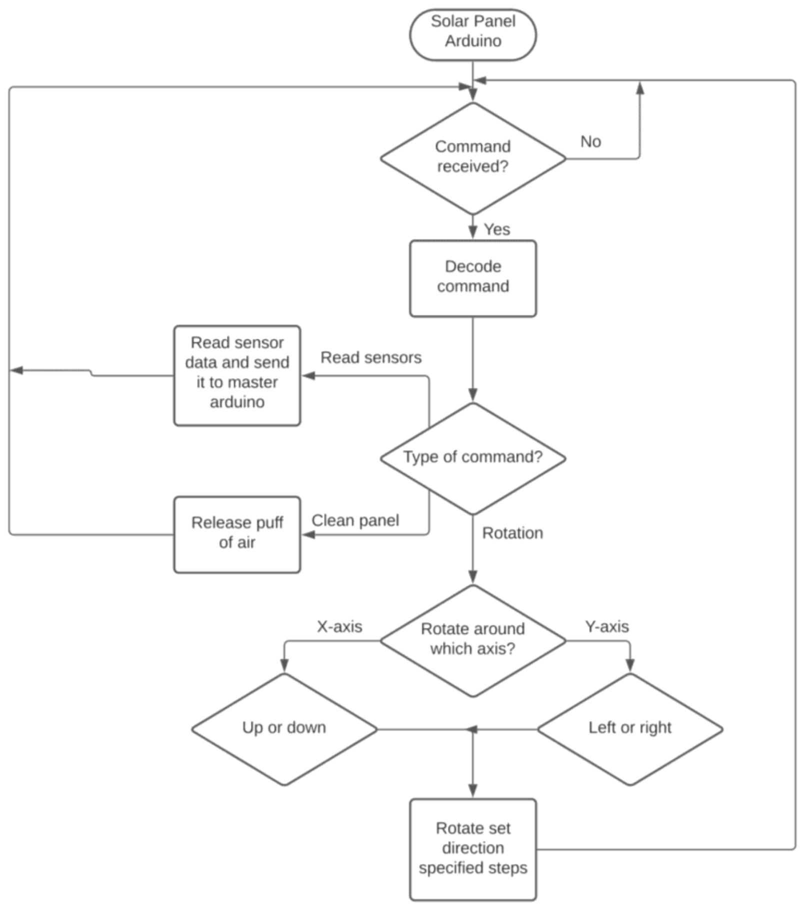
Software top-down design stemmed from the graph immediately below. The picture depicts how our Host PC talks to and interacts with our Master Arduino.


FPV Transmitter
FPV Camera
FPV Reciever
User Interface
Communication Arduino
Transciever (Laptop)
Transciever (Bot)
Master Arduino
Sensor Data
Potentiometer Data
Encoder Data
Temperature Data
Light Data
Solar Panel Data
Solar Controls
Solar Systems
Stepper Motor, Solenoid, Vertical movement
Solar Diagnostics
Motors
Motor Controls
Motor Diagnostic Commands
Motor Data Requests
Legend:
Data In
Data Out
Sensor/Module
Data (write/read)
User Interface
Arduino

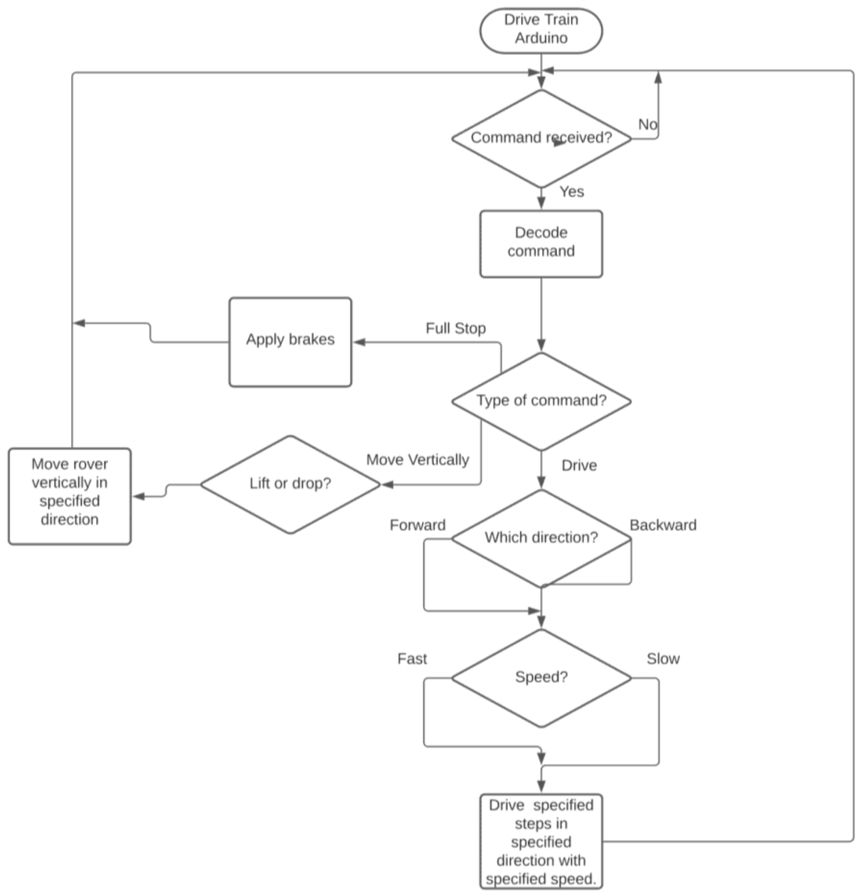

Start Transceiver Code
Has enter been pushed on the console?
No
Yes
Send ping to receiver
Send command to receiver
Reply received?
No
Wait 5 seconds
Yes
Print received data
Command entered?
Yes
No


Start Receiver Code
Message received?
No
Send pong to Transceiver
Yes
Perform relavent command
Send data to receiver
Data to send back?
Yes
No

The above diagram represents the code structure of the pc side transceiver and the rover side receiver which is also the master arduino. This code implements a ping pong structure where a blank message is constantly exchanged between the two devices to ensure that a connection is constantly being held. When a command is issued or data needs to be sent to the transceiver, the empty ping is replaced by a command or data and the other device waits on standby until another blank message is received, or a timeout occurs.



This diagram represents the code functionality of the solar panel system. The solar panel can pivot both left and right, as well as adjust its vertical angle to best capture the sun’s light. This device’s coe implements this functionality by receiving commands from the master and decoding the instruction to achieve the desired rotation and angle pitch.



The drive train subsystem represents the ability of the rover to travel and steer towards a desired location. The device on which this code is implemented achieves this functionality of decoding messages received from the master and executing instructions that are desired by the end user. The end result is a functioning drive system which can be controlled from the user's PC.

Outreach

Due to the COVID-19 pandemic, the NDSU X-Hab team was unable to get into our local tribal schools or public schools to complete outreach activities. The team shifted mindset to how the return on investment for outreach could be maximized and settled on helping to develop a module that will be deployed this summer during an in-person STEM camp for grades 9-12. The team has purchased VEX Robotics classroom kits and have developed a lesson plan to be implemented over four three-hour long sessions during the camp. The camp will host approximately 20 high school students in this first year. The idea is to continue to use the kits and module in the future for this new camp as well as to enhance the outreach activities of student groups on campus such as The Society of Women Engineers.

The module the team developed will involve teams of 4-5 students going through a very abbreviated engineering design process to create a robot that can move obstacles and level out terrain. The idea is to mimic what the Pathbuilder rover will do on the Moon in a small-scale Lego style remote controlled robot. Each team will be given the instruction on how to make a basic robot that can move but will need to design the attachments or add-ons that will accomplish the mission of moving obstacles and leveling terrain.

[1] *Lion Energy 400-Watt Solar Panel Kit.* [Online]. Available: https://shopsolarkits.com. [Accessed: Nov. 2020].
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[5] Ronald A. Creel (2007). "Applying Thermal Control Experiences on Apollo Lunar Rover Project to Rovers for Future Space Exploration," Apollo Lunar Surface Journal. [Online]. Available: https://www.hq.nasa.gov/alsj/alsj-lrvdocs.html. [Accessed: Nov. 2020].
[6] *EK-Cryofuel.* [Online]. Available: https://www.ekwb.com. [Accessed: Nov. 2020].
[7] Atila Gobor (2017). "Radiators Part 2: Performance," EKWB. [Online]. Available: https://www.ekwb.com/blog/radiators-part-2-performance/. [Accessed: Nov. 2020].
[8] "NASA Technical Standard NASA-STD-5001B: Structural Design and Test Factors of Safety for Spaceflight Hardware," National Aeronautics and Space Administration. [Online]. Available: https://standards.nasa.gov/. [Accessed: Nov 2020].
[9] Budynas, Richard G., J. Keith Nisbett, and Joseph Edward Shigley. 2011. Shigley's mechanical engineering design. New York: mcgraw-Hill.