

Rover Chassis & Suspension

Team Phobos

4 Students

Final Design Review

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Mechanical Engineering Department
California Polytechnic State University, San Luis Obispo

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Rover Chassis and Suspension

Project Overview

Team members:

- [REDACTED]
- Nikki Zainer
- [REDACTED]

Key Stakeholders:

- Cal Poly HSTAR (Sponsor)
- SpaceX (Sponsor)
- URC Judges
- Team Phobos

Problem Statement:

The University Rover Challenge (URC) is a robotics competition organized by the Mars Society in which student teams design and build the next generation of Mars rovers. Cal Poly Human Space Technology and Research (CP-HSTAR) has inherited a rover built by an earlier senior design team and is looking to refine its structure and integrate a robotic arm. The next rover iteration will address issues regarding the structural integrity of the suspension, increase traction in the wheels, and introduce an enclosed and modular chassis structure for the electronics.

Design Description

	Description
Suspension	The suspension will be made up of linkages and brackets machined from an aluminum sheet, a spring mechanism, and various fasteners for each pivot point.
Chassis	The chassis will have a frame made from aluminum extrusions, plexiglass side panels, and an aluminum bottom panel. Additional features can be added to attach other subsystems.
Differential	The differential uses a pivoting bar mounted to the top of the chassis. It is actuated through connecting rods to the suspension hubs.
Wheels	The wheels will be 3D-printed and feature an elliptical spoke design to absorb shock. A rubber tread will be installed to improve traction.

Key Specifications

Specification	Target
System Weight	35 kg
System Dimensions	1.2 x 1.2 x 1.2 m
System Cost	\$4,000
Time to Replace Parts	10 Minutes
Maximum Part Deflection	5 mm

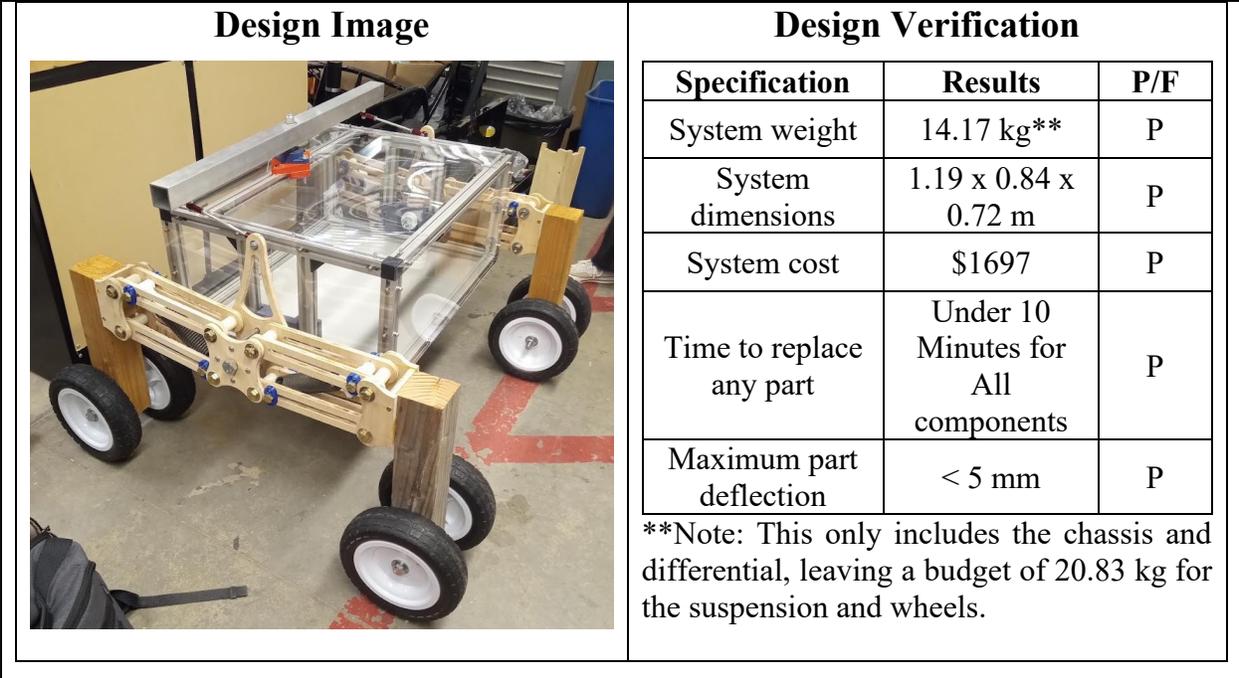


Figure 1. Four-Panel Chart.

1 Overview

The Mars rover project is part of the University Rover Challenge (URC), a robotics competition organized by the Mars Society that tasks student teams with designing and building the next generation of Mars rovers. Cal Poly Human Space Technology and Research (CP-HSTAR) has inherited a rover developed by a previous senior design team, as shown in the figure below.

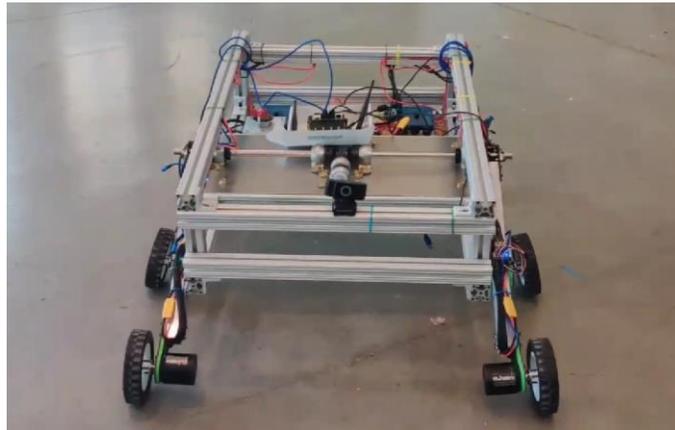


Figure 2. Impassibility Rover produced by previous senior design team.

This report documents the progress made in refining the rover's structure, highlighting key specifications, and detailing design improvements aimed at enhancing the suspension's structural integrity, improving wheel traction, increasing modularity, and developing an enclosed chassis for electronic components.

This report includes a detailed breakdown of the rover's chassis, differential, and suspension design. As well as the implementation of the verification prototype, design verification results, and future work required to optimize the prototype. The appendices provide supporting documentation such as the user manual, risk assessment, budget, and test procedures.

2 Concept Description

Our design addresses our original design improvement goals mentioned in the Overview section. Figure 3 below shows a detailed isometric CAD model of our full system. Each subsection will detail the design for each specific subsystem labeled in this figure.

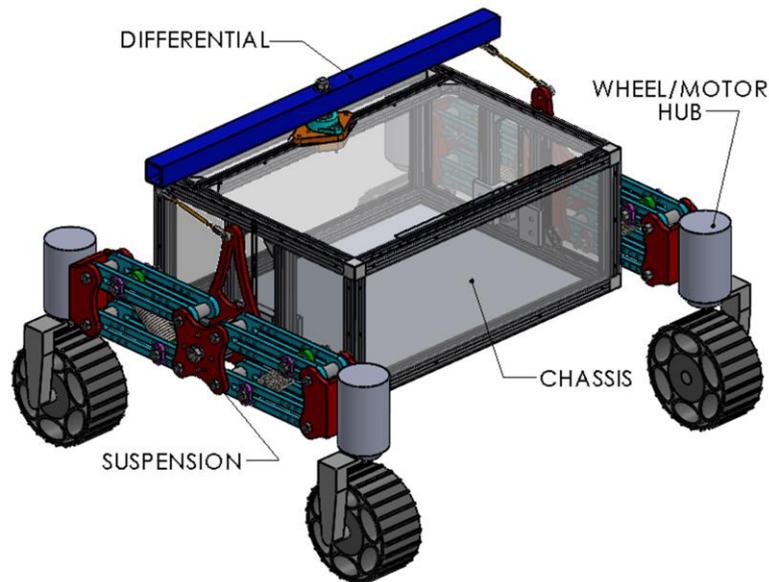


Figure 3. Labeled isometric CAD assembly of full rover system.

2.1 Chassis

The chassis is constructed out of aluminum extrusions due to them being highly modular, lightweight, and the lack of welds being necessary, which reduces potential points of failure. In addition to the bars composing the outer edges of the frame, additional bars are added to the left and right sides of the chassis to act as mounting points for the center bracket. Additionally, another bar on the top of the frame is implemented, to function as a mounting point for the pivot bar of the differential. In addition to the frame, large removable side panels are added to encase the frame to protect it from dust. The panels on the top, front, back, left, and right sides of the frame are made from thin plexiglass to minimize weight, while the plate mounted on the bottom of the frame is made from thicker aluminum. This bottom plate works to better protect the internal components from dust and rocks kicked up during operation.

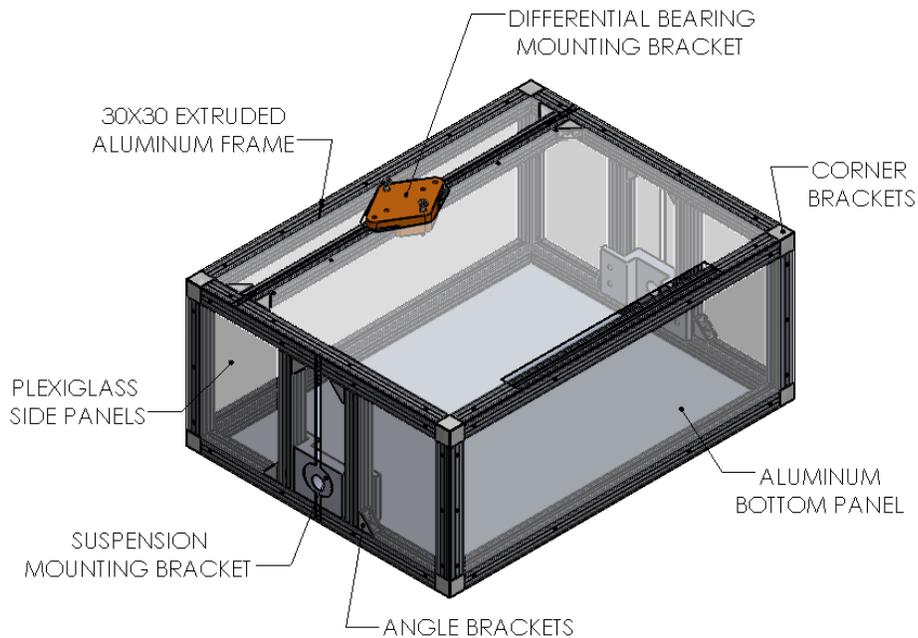


Figure 4. Labeled isometric CAD assembly of the chassis subsystem.

2.2 Differential

The differential features a pivoting bar design mounted on the top of the rover chassis. This pivoting bar is mounted on a bearing, and its ends are connected to the suspension system via ball-joint rod-end links. As each side of the suspension rotates, the differential will average the difference in rotation between each side of the rover. This functions to keep the chassis level. This system saves space on the interior of the chassis by removing the need for a gear box mounted inside the chassis. It also is less sensitive to dust and requires fewer bearings than a bevel gear system. All components have been sized to support the load generated by the rover under maximum acceleration. The end links include spacers to prevent a moment load on the bearing that may cause misalignment. Aluminum was chosen, when possible, to save weight. Any non-aluminum fasteners are zinc-plated to reduce the risk of galvanic corrosion. The flange bearing requires periodic greasing based on the usage conditions.

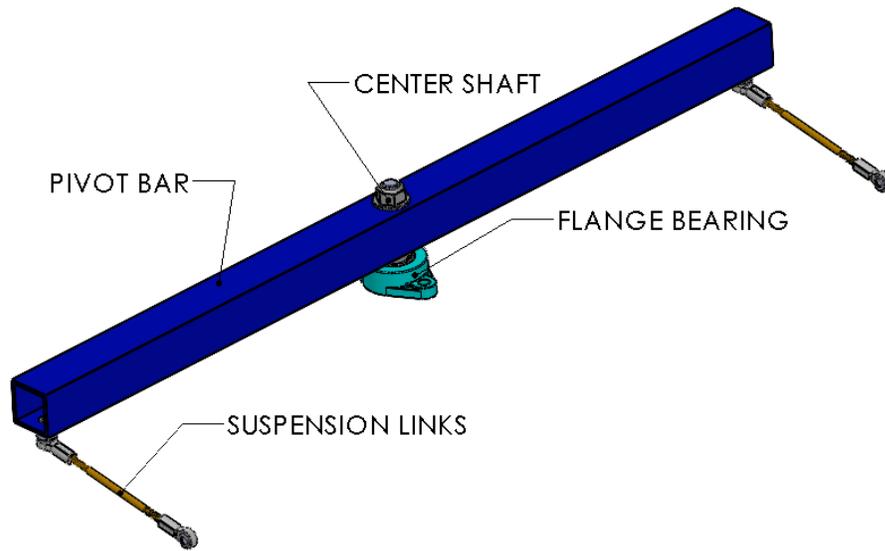


Figure 5. Labeled isometric CAD assembly of the differential subsystem.

2.3 Suspension

The suspension system consists of linkages that are mounted to each wheel hub as well as the center bracket. Those connection points will function as pivot points that allow the suspension linkages to rotate as weight is added to the chassis and as shock loads are experienced during operation. The suspension linkages and brackets will be made from stock aluminum sheet to ensure that those components are both durable and lightweight. Two suspension linkages will be connected to each other by a spring mechanism, which mitigates shock loading. As weight is added to the chassis in the center, the bracket will be forced downwards. In doing so, the spring mechanism will engage allowing the suspension linkages to be supported as they pivot to accommodate the weight. To ensure that the spacing is appropriate between the damper and linkages, as well as the center bracket and chassis, various nuts, bolts, and spacers will be used to assemble all pivot points. Standoffs will also be used to locate the two plates that form the center bracket together.

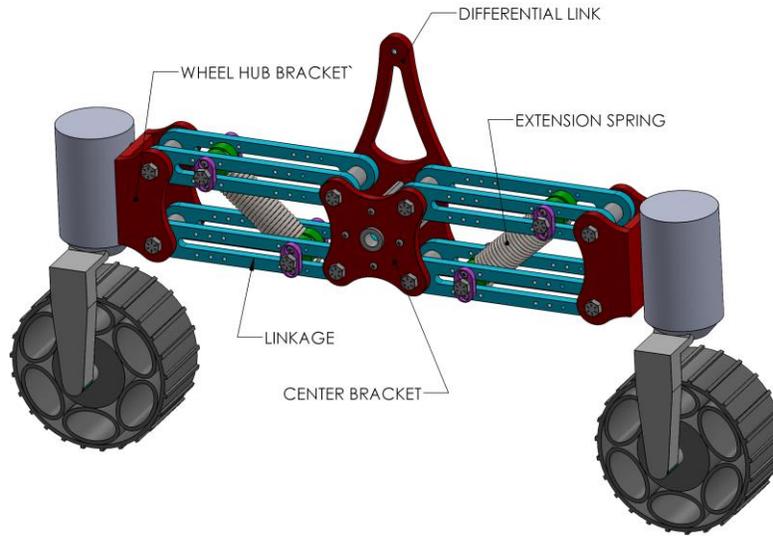


Figure 6. Labeled isometric CAD assembly of the suspension subsystem.

2.4 Wheel Hub

Though we were unable to manufacture the wheel hub and its components, we have included this section since we did get to the design phase of this subassembly. The wheel hub will be comprised of the wheels themselves as well as the housing for the driving and steering motors. The wheel design is still in progress as our team plans to 3D print our own design. Additionally, calculations for sizing the motors based on the required torque, power, and speed of the rover have also been underway. We would also like to note that holonomic drive for steering was determined to be a stretch goal in our PDR, which was also factored within our calculations.

2.4.1 Wheels

The wheels are designed to be 3D printed and will have a rubber tread adhered to the outer surface of the wheel. The wheels have an impact absorbing elliptical spoke design, shown in Figure 8. These spokes function as springs and will reduce the amount of force transmitted to the suspension and chassis when experiencing an impact.

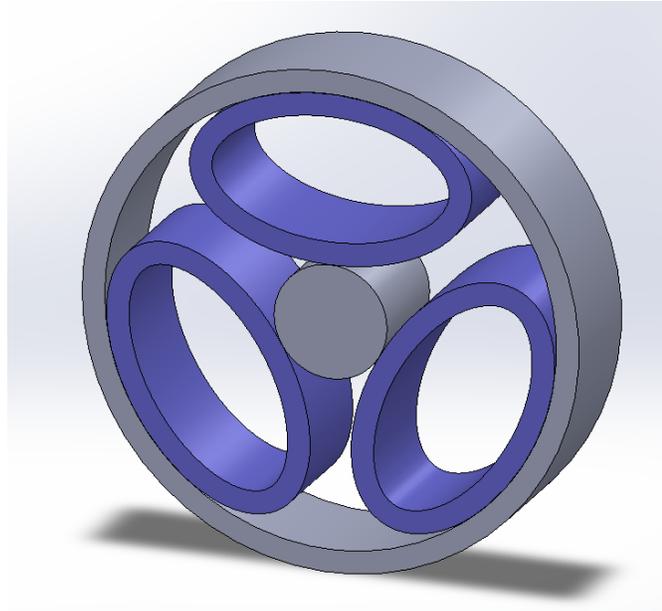


Figure 7. Shock absorbing wheel mockup isometric view.

2.4.2 Motors

After calculating the required torque and speed at the wheel drive shaft see below in Appendix D, considering terrain conditions and slopes the rover must traverse, we compared our desired torque after the gear output with stall torque and speed of the chosen motor from Rev Robotics to identify the most suitable brushless motor within a reasonable price range. Additionally, we factored in inefficiencies by selecting a motor capable of outputting at least 5-10% more power than calculated. Based on our analysis, we concluded that the Neo Brushless Motor V1.1 is well-suited for our rover's requirements. We have decided to use the same type of motor for both the driving and steering motors.

3 Implementation

Once we finalized our design, analyzed it, and determined the components required for our final assembly, we moved on to the manufacturing process. We utilized processes such as water jet cutting, laser cutting, lathe operations, CNC milling, and 3D printing to manufacture our required components. Examples of this can be seen below.

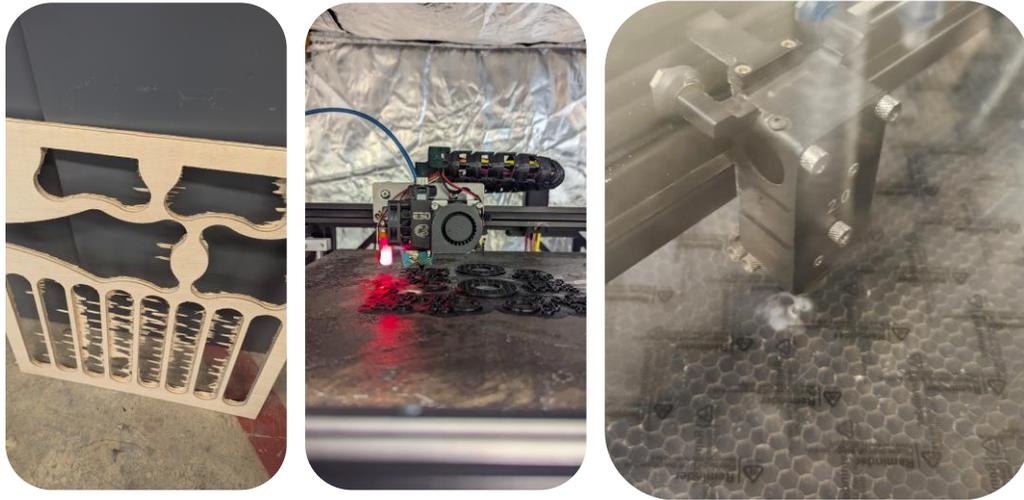


Figure 8. Manufacturing processes from left to right: CNC milling, 3D printing, and laser cutting.

For the chassis, we purchased the aluminum extrusions to the length we required, then had to tap the holes on either end of each piece to create mounting points for the corner brackets. The bottom aluminum panel was cut to size using a water jet. The plexiglass side panels were originally supposed to be cut using the water jet but because they were so thin, they were cut using a laser cutter. Both processes were done using resources provided by at the Mustang 60 shop. The suspension and differential brackets were 3D printed.

The pivot bar for the differential was made by drilling holes in an aluminum stock bar. The center shaft was turned using a lathe. The bar and shaft were then mounted to a flange bearing. There is potential for improvement by adding a hole on the radius of the shaft to aid in tightening the nut on the end of the shaft. End links and rods were purchased from McMaster Carr and used to attach the differential to the suspension.

Components for the suspension including the center brackets, wheel hub brackets, and linkages were cut out of a 1/2" plywood sheet using a CNC mill at the Innovation Sandbox. Additionally, the components used to hold the spring mechanism in place were 3D printed. We ran into issues regarding the fact that the springs came with the loops perpendicularly oriented rather than parallel, resulting in the design of another spacer to hold the springs in place along with the original spacers which is shown in Figure 10. This resulted in additional manufacturing time, but ultimately was required to address an issue from the product description on McMaster Carr not being completely accurate.

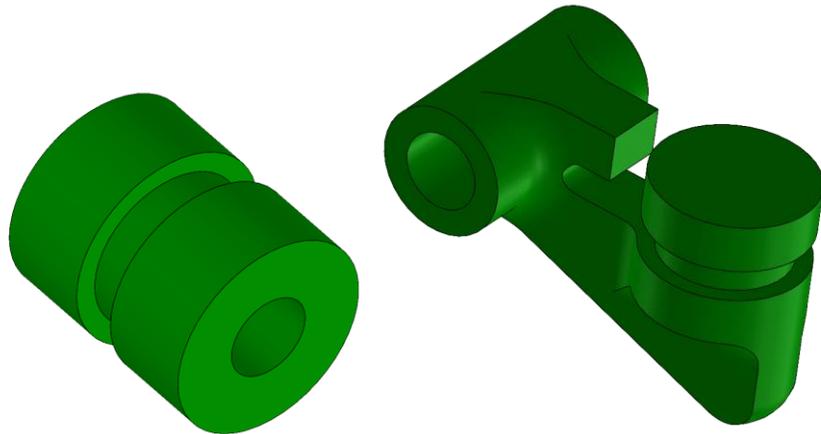


Figure 9. Original spring spacer (left) and perpendicular spring spacer (right).

Once all custom parts were manufactured and stock parts and fasteners were ordered, our final prototype was assembled, which is shown in the figure below.

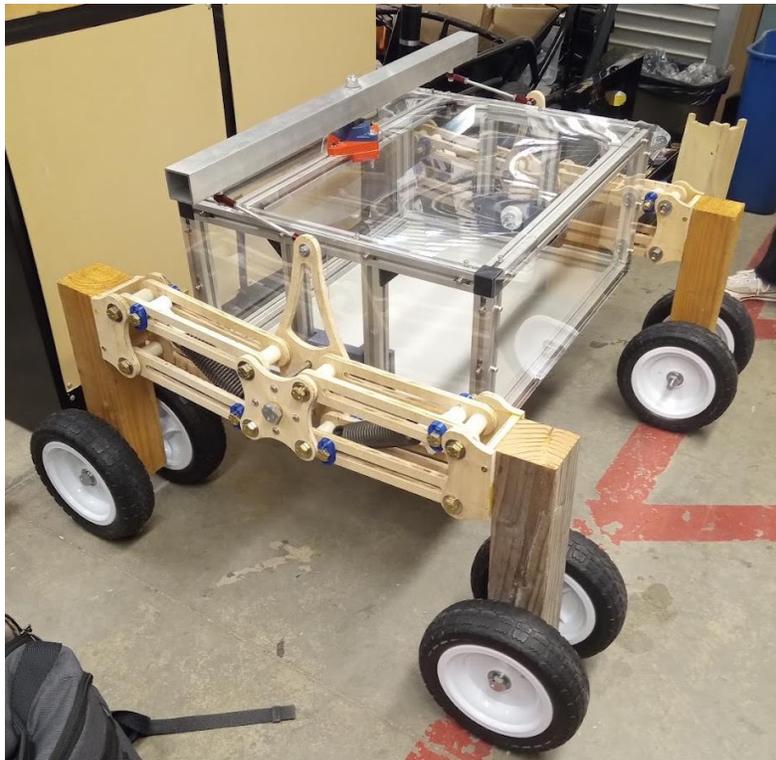


Figure 10. Final prototype of rover.

The completed verification prototype includes a completed chassis and differential. The suspension is currently a wood mockup intended to verify the final suspension design before the final suspension is waterjet out of an expensive plate of aluminum. Due to budget, the motors

could not be purchased for the verification prototype. 4x4 blocks are used in their place to provide mounting points for the wheels and to emulate the weight of the drive system. We also were not able to manufacture our wheels, but did discover that a double wheel design would be more efficient to create more surface contact and stabilize the rover.

4 Design Verification

To verify our design, we had to ensure that our design met each of our specifications, which are listed below.

Table 1. Engineering specifications

Spec. #	Specification Title	Specification Description	Target (Units)	Tolerance	Risk*	Compliance**
1	System Weight	Per URC guidelines [1]. The final mass will be weighed on a scale.	35 kg	Max	H	A, I
2	System Dimensions	Per URC guidelines [1]. Dimensions will be measured.	1.2 x 1.2 x 1.2 m	Max	H	I
3	Total System Cost	Per URC guidelines [1]. Cost will be tracked and budgeted.	\$4,000	Max	H	I
4	Time to Replace any Part	The time required to switch a part of the rover for a new one.	10 Minutes	Max	M	T
5	Maximum Part Deflection	The displacement of a part when loaded compared to unloaded.	5 mm	Max	H	A, I
Design Assumptions***						
i	Main Body Acceleration	The acceleration experienced by the main body determines the force experienced by suspended components. Determined by using the desired acceleration time and the average speed of two existing URC rovers	0.75 m/s ²	Max	M	A, T
ii	Reliability	A constraint to prevent premature failure.	90%	Min	M	A
iii	Factor of Safety	A constraint to protect from conditions exceeding expectations.	1.5	Min	M	A
iv	Traction	Instances in which wheel-to-ground contact is maintained in sloped and sandy terrain	100%	Min	M	I, T

*Risk of meeting specification: (H) High, (M) Medium, (L) Low

** Compliance Methods: (A) Analysis, (I) Inspection, (S) Similar to Existing, (T) Test

***Assumptions used for design analysis/calculations, therefore will not be tested.

Table 2 shows a summary of our test results. Detailed descriptions of each test can be found in Appendix F.

Table 2. Test results.

Specification	Results	Pass/Fail
System weight [Spec 1]	14.17 kg*	Pass
System dimensions [Spec 2]	1.19 x 0.84 x 0.72 m	Pass
System cost [Spec 3]	\$1697	Pass
Time to replace any part [Spec 4]	Under 10 Minutes for All components	Pass
Maximum part deflection [Spec 5]	< 5 mm	Pass
Maximum Spring Deflection	12 mm	Pass

*Note: This only includes the chassis and differential, leaving a budget of 20.83 kg for the suspension and wheels.

As shown in the table above, our rover passed our weight and dimension constraints as set by the URC guidelines. Because the suspension was manufactured using wood, only the mass of the chassis and differential were measured. The suspension has a total estimated mass of around 15 kg, so the final mass would still fall into our desired specification.

Our indented Bill of Materials can be found in Appendix C to verify our results to meet our system cost specification. It should be noted that this budget accounts for the suspension components being made from stock aluminum rather than wood; therefore, ensuring that our entire system falls beneath our \$4000 budget limit.

The aluminum extrusions were very robust and when conducting our deflection testing, we found that there was extremely minimal deflection when the frame was loaded with weight, which fell under our 5 mm maximum.

Lastly, testing the maximum spring deflection by applying predicted loads that the rover would experience allowed us to ensure the structural integrity of the suspension. This verified that the system would not fail or bow out like the previous Impassibility rover iteration. The springs extended to a maximum of 12 mm, which was well below its maximum rating of 254 mm; therefore, meeting our design improvement goal regarding the structural integrity of the suspension.

5 Conclusion & Next Steps

The Mars rover prototype has been developed to meet the challenges of navigating diverse terrains. Significant progress has been made in designing a robust and functional rover, with a focus on modularity and efficiency.

The next steps for the Mars rover prototype involve several critical design and manufacturing enhancements to optimize its performance and functionality. To improve the structural components, the suspension system will be machined from stock aluminum sheets, ensuring durability and precision. Because the suspension system passed our deflection testing while made out of wood, the components could be designed to be more lightweight to reduce the mass budgeted to this subsystem. A spring-damper mechanism will need to be implemented to mitigate excessive oscillations and vibrations, enhancing stability during uneven terrain traversal. Additionally, wheel hubs will be carefully designed and manufactured to integrate seamlessly with the rover's drivetrain.

For improved traction and adaptability, wheels will be 3D printed and configured with a dual-wheel design to increase surface contact, providing better performance on diverse surfaces. Motors and electronic components will be integrated to power and control the rover, with chassis dimensions adjusted as necessary to accommodate these additions. These steps collectively aim to refine the prototype, ensuring it meets the requirements of the University Rover Challenge and improve upon the functionality of the rover.

Appendices

- A. User Manual
- B. Risk Assessment
- C. Budget
- D. Motor Selection & Specifications
- E. DVP&R
- F. Test Procedures

Appendix A – User Manual

Safety

All shop safety protocols must be followed for all manufacturing and assembly operations.

PPE

- Safety glasses
- Closed-toed shoes
- Pants
- Tie long hair
- Remove any rings, necklaces, etc.

Manufacturing

Chassis

Extrusions:

- Cut 30x30 Standard (HFS) Aluminum Extrusions to following lengths:
 - 490 mm (x4)
 - 660 mm (x5)
 - 240 mm (x8)
- Tap both ends of following extrusions:
 - 490 mm (x4)
 - 660 mm (x4)
 - 240 mm (x4)

Mounts:

- Print Mounting Brackets for interfacing with other systems:
 - Shaft Mount (x2)
 - Differential Mount (x1)
 - Lead Screw Mount (x6)

Panels:

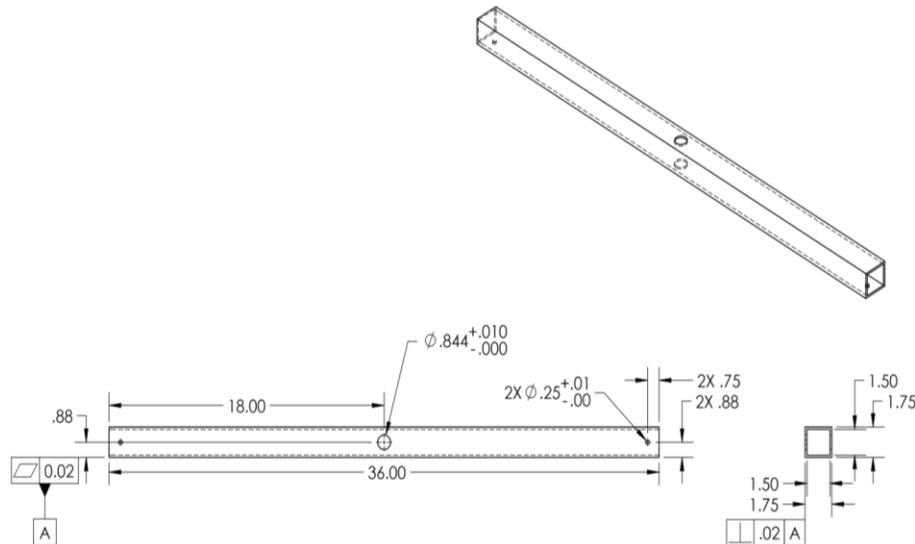
- Cut Panels from stock Material:
 - Aluminum (1/8 in Thickness)
 - Bottom Panel (x1)
 - Plexiglass (0.04 in Thickness)
 - Side Panel (x2)
 - Front Panel (x1)
 - Back Panel (x1)
 - Top Panel (x1)

Suspension

- Cut suspension components from stock sheet material
 - CB Back Plate (x2)
 - CB Front Plate (x2)
 - Linkage (x16)
 - Wheel Hub Bracket (x16)
- **This requires a .DXF or .DWG for each suspension component.
- Sand and finish suspension components.
- Tap holes for standoffs on CB back plates.
- Tap holes for spring brackets on linkages.

Differential

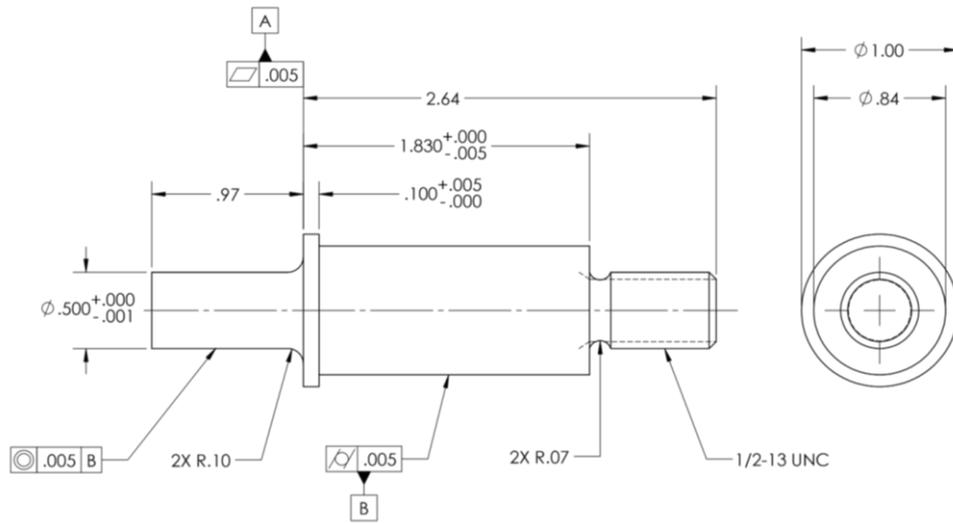
Pivoting Bar



Drill Press:

- Using a 27/32 in. bit, drill a hole through the top and bottom face, centered along the length and width of the tube.
- Using a 1/4 in. bit, drill two holes through the bottom face of the tube, centered along the length of the tube and 3/4 of an inch from the ends of the tube.

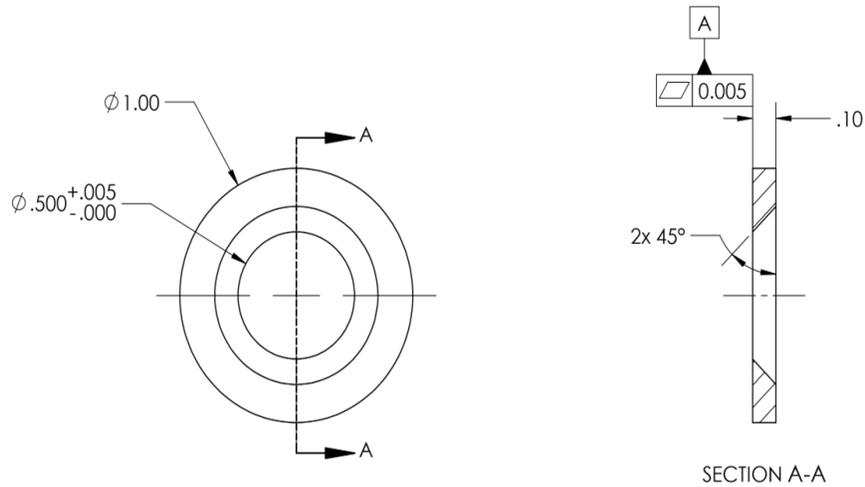
Center Shaft



Lathe:

- Turn the aluminum rod the minimum amount required to eliminate the raw finish and establish a datum on the outer diameter.
- Face one end of the rod the minimum amount required to flatten it.
- Cut off the rod at 3.61 inches.
- From the flat end of the rod, turn a .87 inch long section down to a 1/2 inch diameter.
- Face the remaining .10 inches of the section down to .6 inches in diameter.
- Using a convex cutting tool create the .1 in radius at the shoulder.
- On the other end of the rod turn the diameter down to 0.84 inches, leave a .1 inch shoulder.
- Turn down a .81 inch section from the end of the rod to 1/2 inch diameter.
- Using a round grooving tool cut a .07 inch radius thread relief into the rod.
- Thread the end section of the rod with 1/2-13 threads.

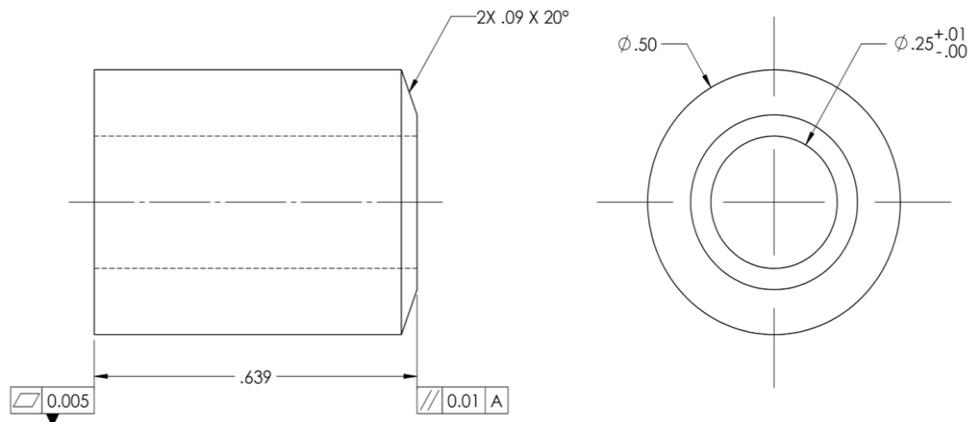
Shaft Collar



Lathe:

- Use the remaining stock from the center shaft
- Drill a 1/2 inch hole in the rod to a depth of .1 inch
- Chamfer the inner diameter of the hole to a depth of .1 inch
- Cut off the Shaft Collar at .1 inches.

End Link Spacer



Lathe:

- Turn the aluminum rod the minimum amount required to eliminate the raw finish and establish a datum on the outer diameter.
- Face one end of the rod the minimum amount required to flatten it.
- Chamfer the end of the rod at a 20-degree angle
- Cut off the rod at 0.639 inches.
- Drill a 1/4-inch hole through the cutoff End Link Spacer beginning at the chamfered end.

Motor Hub & Wheel

Cut motor hub components from stock sheet material

- 8 (3 x 6 inches) plates with two 0.75 inches holes.
 - Machined the plate to look similar to the profile of suspension components.
 - Each of the 0.75 inches holes are positioned at $\frac{3}{8}$ from two edges.
- 4 (3.375 x 4.5 inches) plates.
- Drill $\frac{1}{8}$ Pilot holes in all the plates at intersecting positions.
- Drill $\frac{5}{8}$ holes in 4x4 for $\frac{5}{8}$ bolts for wheel attachment.

Assembly

Chassis

Frame

- Attach tapped extrusions together with 6 Series Corner Baskets, 8 total
 - Use 1 bracket in each corner, with holes facing tapped ends
- Attach non-tapped extrusions to frame using 6 Series Reversal Brackets, 8 total
 - 660 mm (x1)
 - Use 4 brackets in total, 2 on each end, on either side of extrusion
 - 240 mm (x4)
 - Use 4 brackets in total, 1 on each end, on 1 side only

Mounts

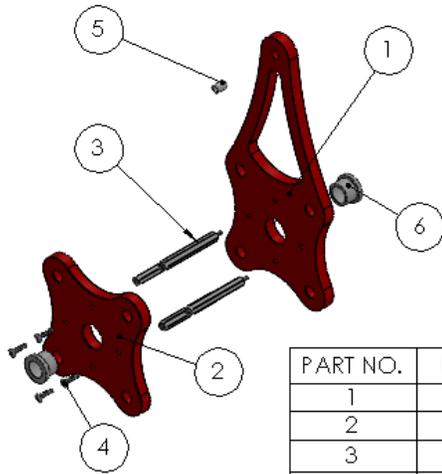
- Attach using 4 mm & 5 mm Thread Diameter Aluminum Extrusion Bolts & 4 mm Thread Diameter Post-Assembly Insertion Nuts and Stoppers
 - Shaft Mount (x2)
 - Use (x8) 4 mm Thread Diameter bolts, nuts, and stoppers, 4 for each mount attached to non-tapped 240 mm extrusions
 - Differential Mount (x1)
 - Use (x4) 4 mm Thread Diameter bolts, nuts, and stoppers, attached to non-tapped 660 mm extrusion
 - Lead Screw Mount (x6)
 - Use (x6) 4 mm Thread Diameter bolts, nuts and stoppers, attached to tapped 660 mm extrusion on front, top section of rover frame
 - Use (x6) 5 mm Thread Diameter bolts to attach lead screw to each mount using built-in nuts along bottom rail

Panels

- Attach using 4 mm Thread Diameter Aluminum Extrusion Bolts & 4 mm Thread Diameter Post-Assembly Insertion Nuts and Stoppers
 - Bottom Panel (x1)
 - Attach using (x20) 4 mm Thread Diameter bolts, nuts, and stoppers
 - Side Panel (x2)
 - Attach using (x14) 4 mm Thread Diameter bolts, nuts, and stoppers for each panel, (x28) total
 - Front Panel (x1)
 - Attach using (x12) 4 mm Thread Diameter bolts, nuts, and stoppers
 - Back Panel (x1)
 - Attach using (x14) 4 mm Thread Diameter bolts, nuts, and stoppers
 - Top Panel (x1)
 - Attach using (x17) 4 mm Thread Diameter bolts, nuts, and stoppers

Suspension

Center Brackets (CB)



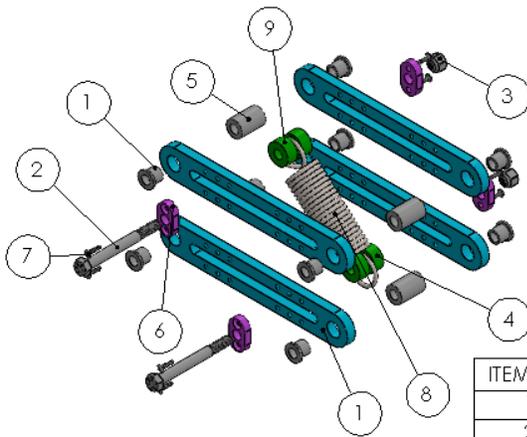
PART NO.	PART NO.	DESCRIPTION	QTY.
1	112200	CB Back Plate	1
2	112100	CB Front Plate	1
3	112500	Standoff	4
4	114200	Vibration-Resistant Sealing Rounded Head Screws	4
5	112300	Differential Sleeve Bearing	1
6	112400	CB Sleeve Bearing	2

- Attach standoffs to CB back plate.
- Line up holes on CB front plate with top of standoffs.
- Secure top plate using #10 washers and #10-32 3/4" sealing rounded head screws.
- Insert sleeve bearings into center holes of both front and back CB plates.

Hub Brackets

- Secure brackets to back plate.
- Secure assembled hub bracket to motor hub.
- Insert sleeve washers into bracket holes.

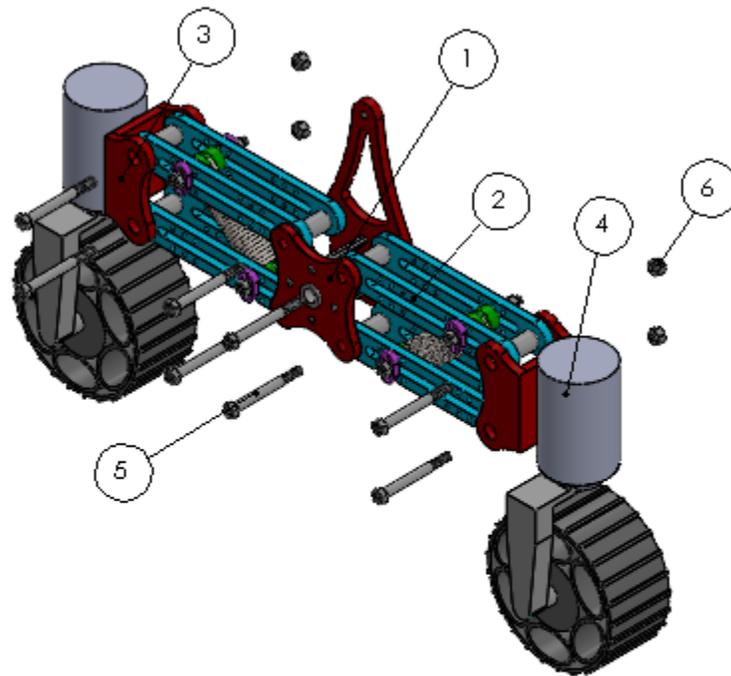
Linkages



ITEM NO.	PART NO.	DESCRIPTION	QTY.
1	111100	Linkage	4
2	114500	Bolt 1/2-20	2
3	114600	Nut 1/2-20	2
4	111300	Spring Spacer	1
5	114700	Off-White Nylon Unthreaded Spacer	4
6	111400	Spring Bracket	4
7	114200	Vibration-Resistant Sealing Rounded Head Screws	8
8	111200	Steel Extension Spring	1
9	111600	Perpendicular Spring Spacer	1

- Insert sleeve washers into linkage holes (x2/linkage).
- Secure spring brackets to linkages (x2/linkage) using #10-32 3/4" sealing rounded head screws (x2/bracket).

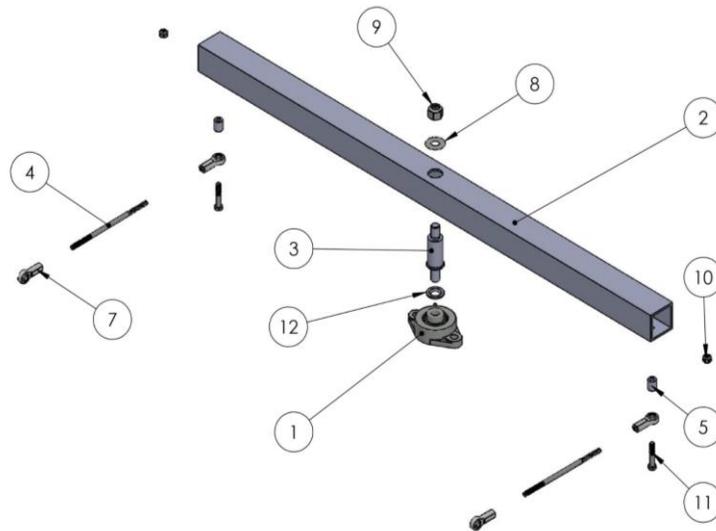
Suspension Subassembly



ITEM NO.	PART NO.	DESCRIPTION	QTY.
1	112000	Center Bracket	1
2	111000	Linkage Subass'y	2
3	113000	Wheel Hub Bracket	2
4	140000	Wheel Hub	2
5	114500	Bolt 1/2-20	12
6	114600	Nut 1/2-20	12

- Secure one side of linkage to CB with 1/2"-20 bolts and unthreaded spacers.
 - Repeat for all 8 linkages for one side of the suspension.
- Secure other side of linkage to Motor Hub with 1/2"-20 bolts/nuts and unthreaded spacers.
- Insert spring between linkages.
- Secure spring through spring brackets using spring spacers and 1/2"-20 bolts/nuts.

Differential



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	121200	Flange Bearing	1
2	121100	Pivoting Bar	1
3	121300	Center Shaft	1
4	122200	Connecting Rod	2
5	122300	End Link Spacer	2
7	122100	End Link	4
8	121500	1/2 Washer	1
9	121600	1/2-13 Nut	1
10	122410	1/4-28 Nut	2
11	122420	1/4-28 Bolt	2
12	121400	Shaft Collar	1

- Place the aluminum bar on the center shaft and securing using 1/2" washer and nut.
- Place the shaft collar on the shaft and place the shaft into the flange bearing. Secure using the set screws in the flange bearing.
- Fully thread the end links (4x) onto each end of the connecting rods (2x).
- Place the assembled end links and connecting rods onto the 1/4" bolts.
- Place the end link spacers (2x) onto the bolts with the chamfered ends towards the end links.
- Put the bolts with the linkages through the holes in the ends of the aluminum bar and secure using the 1/4" nuts.

Motor Hub & Wheel

- Attach the 3.375 x 4.5 plate between two (3x6) plates using 1/8 wood screws.
 - Repeat 3 more times
- Attach the plates to 4x4 blocks wood using 1/8 wood screws.
- Use the 5/8 bolts to attach the purchased wheels with bearings included. (nuts, washers)

System Assembly

- Attach all separate components using interface brackets, material, and bolts
- Ensure parts do not clash or interfere

Differential to Chassis

- Using m10 bolts attach the differential to the mounting bracket
- Bolt the mounting bracket to the center of the aluminum extrusion on the top of the chassis
- Attach the connecting rods to the suspension using 1/4" bolts

Suspension to Hub

- Ensure center of suspension is supported.

- Secure each linkage to hub brackets using $\frac{1}{2}$ "-20 bolts/nuts and unthreaded spacers.

Suspension to Chassis

- Insert $\frac{3}{4}$ " sleeve bearing into side mount bracket on chassis.
- Ensure both the center of the suspension

Maintenance & Repair

To repair any structural components of the rover, the part may be removed, remanufactured, and replaced. To remove a part, refer to the dedicated section of the user manual, follow the manufacturing instructions recreate the component if needed, and relace the part following the assembly instructions.

Appendix B – Risk Assessment

Mars Rover

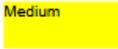
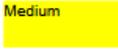
5/19/2024

Risk Level Report

Application: Mars Rover Analyst Name(s): Aung Bhone Zaw
 Description: Testing Company:
 Product Identifier: Facility Location:
 Assessment Type: Detailed
 Limits:
 Sources:
 Risk Scoring System: ANSI B11.0 Two Factor

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Final Assessment				Initial Assessment		Status / Responsible /Comments /Reference	
Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System		Severity Probability
Serious		1-1-1	operator normal operation	mechanical : crushing dropped parts (frames)	use proper lifting techniques and equipment with enough team members	Serious Likely	High
Minor		1-1-2	operator normal operation	mechanical : cutting / severing sharp edges and comers		Minor Likely	Low
Catastrophic		1-1-3	operator normal operation	material handling : motor vehicle movement false start due to motors		Catastrophic Unlikely	Medium
Moderate		1-2-1	operator clean up	mechanical : pinch point moving parts (gears)		Moderate Likely	Medium
Serious		1-3-1	operator basic trouble shooting / problem solving	mechanical : unexpected start motor/battery wired		Serious Unlikely	Medium
Catastrophic		1-3-2	operator basic trouble shooting / problem solving	material handling : motor vehicle movement impact with obstacles/person	Use signs and cones to warn passer by not to walk near the testing area. Could add some sensors.	Catastrophic Likely	High
Serious		2-1-1	CPHSTAR CLUB adjust controls / settings / alignment	mechanical : crushing collapsing chassis	Conduct regular structural integrity checks	Serious Likely	High

Final Assessment						Initial Assessment		Status / Responsible /Comments /Reference
Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Severity Probability	Risk Level	
Minor		2-1-2	CPHSTAR CLUB adjust controls / settings / alignment	mechanical : cutting / severing Tool Misuse		Minor Likely	Low 	
Serious		2-1-3	CPHSTAR CLUB adjust controls / settings / alignment	mechanical : drawing-in / trapping / entanglement Loose Clothing/Hair in moving parts	Always tie long hair back and enforce dressing code like no loose clothing. Could add guards on moving parts.	Serious Likely	High 	
Moderate		2-1-4	CPHSTAR CLUB adjust controls / settings / alignment	mechanical : pinch point suspension system/ wheel assembly / joints		Moderate Likely	Medium 	
Minor		2-1-5	CPHSTAR CLUB adjust controls / settings / alignment	slips / trips / falls : trip tools on ground		Minor Likely	Low 	
Catastrophic		2-2-1	CPHSTAR CLUB periodic maintenance	material handling : motor vehicle movement impact with obstacles/person	Use signs and cones to warn passer by not to walk near the testing area. Could add some sensors.	Catastrophic Likely	High 	
Catastrophic		2-3-1	CPHSTAR CLUB trouble-shooting / problem solving	mechanical : unexpected start Faulty wiring		Catastrophic Unlikely	Medium 	
Minor		3-1-1	Future Team (Control and Electronics) repair / replace wiring / systems	mechanical : cutting / severing maintenance tool		Minor Likely	Low 	
Serious		3-1-2	Future Team (Control and Electronics) repair / replace wiring / systems	mechanical : drawing-in / trapping / entanglement Loose Clothing/Hair in moving parts	Always tie long hair back and enforce dressing code like no loose clothing. Could add guards on moving parts.	Serious Likely	High 	

Final Assessment						Initial Assessment		Status / Responsible /Comments /Reference
Severity Probability	Risk Level	Item Id	User / Task	Hazard / Failure Mode	Risk Reduction Methods /Control System	Severity Probability	Risk Level	
Moderate		3-1-3	Future Team (Control and Electronics) repair / replace wiring / systems	mechanical : pinch point suspension system/ wheel assembly / joints		Moderate Likely	Medium	
Catastrophic		3-1-4	Future Team (Control and Electronics) repair / replace wiring / systems	electrical / electronic : unexpected start up / motion software glitch		Catastrophic Unlikely	Medium	
Moderate		3-2-1	Future Team (Control and Electronics) grounding panels / controls / machinery	mechanical : cutting / severing sharp edges		Moderate Likely	Medium	
Serious		3-3-1	Future Team (Control and Electronics) install / test / repair circuit	electrical / electronic : power supply interruption Battery Failure		Serious Unlikely	Medium	
Minor		4-1-1	passer by / non-user walk near machinery	slips / trips / falls : trip Tools on the ground		Minor Likely	Low	

Appendix C – Final Budget

Rover Chassis and Suspension Indented Bill of Material (iBOM)

Assy Level	Part Number	Descriptive Part Name	Qty	Part Cost	Total Cost	Source	URL	More Info
		Lvl0 Lvl1 Lvl2 Lvl3 Lvl4						
0	100000	System Assy				-----		
1	110000	Suspension Assy	2	\$ 215.14	\$ 430.28	-----	https://www.i	12"x48" Sheet 1/2" thick**
2	111000	Linkage Assy			\$ -	Custom		** Manuf. fr sheet
3	111100	Linkage	16		\$ -	Custom		** Manuf. fr sheet
3	111200	Spring	4	\$ 16.77	\$ 67.08	McMaster	https://www.i	Extension Spring
3	111300	Spring Spacer	8		\$ -	Custom		3D Print
3	111400	Spring Bracket	16		\$ -	Custom		3D Print
3	111500	Pivot Sleeve Washer	32	\$ 0.50	\$ 16.00	McMaster	https://www.i	(32) Pack of 25 \$12.50
2	112000	Center Bracket			\$ -	-----		
3	112100	CB Front Plate	2		\$ -	Custom		** Manuf. fr sheet
3	112200	CB Back Plate	2		\$ -	Custom		** Manuf. fr sheet
3	112300	Diff Sleeve Bearing	2	\$ 6.51	\$ 13.02	McMaster	https://www.i	For Differential
3	112400	CB Sleeve Bearing	4	\$ 17.18	\$ 68.72	McMaster	https://www.i	Susp-Chassis
3	112500	Standoff	8	\$ 11.62	\$ 92.96	McMaster	https://www.i	CB
2	113000	Wheel Hub Bracket	4		\$ -	Custom		
2	114000	Fasteners			\$ -	-----		
3	114200	Screws	40	\$ 1.66	\$ 66.40	McMaster	https://www.i	(20) CB Pack of 5 \$8.28
3	114300	Bolt 3/4-16	2	\$ 11.65	\$ 23.30	McMaster	https://www.i	CB
3	114400	Nut 3/4-16	2	\$ 1.63	\$ 3.26	McMaster	https://www.i	(2) CB Pack of 5 \$8.16
3	114500	Bolt 1/2-20	24	\$ 3.68	\$ 88.32	McMaster	https://www.i	(24) Pack of 5 \$18.38
3	114600	Nut 1/2-20	24	\$ 0.64	\$ 15.36	McMaster	https://www.i	(24) Pack of 10 \$6.36
3	114700	Spacer 1/2	16	\$ 2.13	\$ 34.08	McMaster	https://www.i	(8) Pack of 10 \$21.30
3	114800	Washer 1/2	32	\$ 0.15	\$ 4.80	McMaster	https://www.i	Pack of 50 \$7.67
3	114900	Spacer 3/4	2	\$ 4.25	\$ 8.50	McMaster	https://www.i	Pack of 5 \$21.27
1	120000	Differential			\$ -			
2	121000	Pivoting Bar			\$ -			
3	121100	Aluminum Bar	1	\$ 50.29	\$ 50.29	Custom	https://www.i	6546K6
3	121200	Flange Bearing	1	\$ 70.10	\$ 70.10	MiMotion	https://www.i	SKF F2B 008-RM
3	121300	Shaft	1	\$ 15.37	\$ 15.37	Custom	.mcmaster.com	Machined 7075 Aluminum
3	121400	Shaft Collar			\$ -	Custom		
3	121500	Washer	1	\$ 0.44	\$ 0.44	Bolt Depot	https://boltde	1/2 Aluminum Washer
3	121600	Nut	1	\$ 1.31	\$ 1.31	Bolt Depot	https://boltde	1/2-13 Aluminum Locknut
2	122000	Differential Linkages			\$ -			
2	122100	End Links	4	\$ 24.84	\$ 99.36	McMaster	https://www.i	6516K177
3	122110	End Link Seals	4	\$ 8.11	\$ 32.44	McMaster	https://www.i	4737T2
2	122200	Connecting Rods	2	\$ 7.77	\$ 15.54	McMaster	https://www.i	6516K177
2	122300	End Link Spacers	2	\$ 1.70	\$ 3.40	Custom	https://www.i	Machined 6061 Aluminum
2	122400	Fasteners			\$ -			
3	122410	Bolt 1/4 2-1/4	2	\$ 1.69	\$ 3.38	ACE		Diff to Chassis
3	122420	Bolt 1/4 1-1/4	2	\$ 1.59	\$ 3.18	ACE		Diff to Susp
3	122430	Nuts	2	\$ 0.11	\$ 0.22	Bolt Depot	https://boltde	1/4-28 Nut
3	122440	Bolt 1/4 1 1/2	6	\$ 0.31	\$ 1.86	Bolt Depot	https://boltde	1/4-28, 1.5 Inch Bolt
1	130000	Chassis			\$ -			
2	131000	Chassis Frame			\$ -			
3	131100	Aluminum Extrusions			\$ -			
4	131110	0.49 m Extrusions	4	\$ 7.00	\$ 28.00	MISUMI	https://us.mis	HFSL6-3030-490
4	131120	0.66 m Extrusions	5	\$ 9.43	\$ 47.15	MISUMI	https://us.mis	HFSL6-3030-660
4	131130	0.24 m Extrusions	8	\$ 4.27	\$ 34.16	MISUMI	https://us.mis	HFSL6-3030-240
3	131200	Corner Brackets	8	\$ 5.18	\$ 41.44	MISUMI	https://us.mis	HBLCR6-B
3	131300	Angle Brackets	12	\$ 3.83	\$ 45.96	MISUMI	https://us.mis	HBLFSNB6-SET
3	131400	Suspension Bracket			\$ -			
2	132000	Side Panels	2		\$ -			
2	132200	Bottom Panel	1	\$ 48.89	\$ 48.89	Home Depot	https://www.i	308670312
2	132300	Front/Back Panels	2		\$ -			
		Stock Acrylic Panel	1	\$ 39.99	\$ 39.99	Amazon	https://www.i	B0C7VNF5X4
3	132400	Fasteners			\$ -			
4	132410	Screws		\$ 0.79	\$ -	MISUMI	https://us.mis	HCBST6-15
4	132420	Nuts & Stoppers		\$ 0.67	\$ -	MISUMI	https://us.mis	HNTBTSN6-6
1	140000	Wheel Hub			\$ -			
2	141000	Wheel	8	15	\$ 120.00	Harbor Freight		
2	142000	Fastners			\$ 29.25	ACE		
		Screws			\$33.23	ACE		
Total Parts			320		\$ 1,697.04			

Appendix D – Motor Selection & Specification

Motor Selection: Hand calculations on Torque and Power are calculated for motor selection within competition parameters.

Motor Selection

$$\text{acceleration time} = 2 \text{ s} \quad \text{SF} = 1.5 \quad \text{mass} = 50 \text{ kg} \quad r_{\text{wheel}} = 0.127 \text{ m}$$

$$\text{max speed} = \frac{2+1}{2} = 1.5 \frac{\text{m}}{\text{s}}$$

$$a = \frac{1.5}{2} = 0.75 \frac{\text{m}}{\text{s}^2}$$

$$F = ma \\ = 50 \text{ kg} \cdot 0.75 \frac{\text{m}}{\text{s}^2} = 37.5 \text{ N} \quad (\text{force to overcome acceleration})$$

$$F_{\text{wheel}} = \frac{37.5 \text{ N}}{4} \cdot 1.5 = 14.06 \text{ N}$$

$$T_{\text{wheel}} = F_{\text{wheel}} \cdot r_{\text{wheel}} \quad @ \text{ wheel drive shaft} \\ = 14.06 \text{ N} \cdot 0.127 \text{ m} = 1.786 \text{ Nm}$$

$$F = 50 \text{ kg} \cdot 9.81 \frac{\text{m}}{\text{s}^2} \cdot \frac{1}{4} \cdot 1.5 = 183.93 \text{ N} \quad (\text{force required to climb over obstacle})$$

$$T_{\text{max}} = 183.93 \text{ N} \cdot 0.127 \text{ m} = 23.36 \text{ Nm per wheel}$$

$$F_{\text{total}} = 14.06 \text{ N} + 183.93 \text{ N} = 197.99 \text{ N}$$

$$T_{\text{total}} = F_{\text{total}} \cdot 0.127 \text{ m} = 197.99 \text{ N} \cdot 0.127 \text{ m} = 25.146 \text{ Nm} \quad \leftarrow \text{Gear Box Output}$$

Power

$$v = r \cdot \omega$$

$$\omega = \frac{v}{r} = \frac{1.5 \frac{\text{m}}{\text{s}}}{0.127 \text{ m}} = 11.81 \frac{\text{rad}}{\text{s}} = 112.766 \text{ rpm}$$

$$\text{Power} = T \times \omega \\ = 25.146 \text{ Nm} \times 11.81 \frac{\text{rad}}{\text{s}} \\ = 296.97 \text{ W}$$

Motor Specification

The REV Robotics NEO Brushless Motor V1.1

The motor incorporates tapped #10-32 holes in the shaft and rear housing, streamlining pinion retention and installation. Enhanced mounting flexibility is achieved with additional front-face holes, preserving its drop-in compatibility with CIM-style motors. Its high power-to-weight ratio, integrated encoder (42 counts/rev), and motor temperature sensor provide advanced performance monitoring. Optimized for the SPARK MAX Motor Controller, the NEO V1.1 is designed for precision, featuring pre-pressed pinion options for EVO Shifter transmissions and CIM Sport gearboxes. With 406 W maximum power, 2.6 Nm stall torque, and high-temperature neodymium magnets, it delivers reliability and robustness.

Table 3: Specifications for Neo V1.1

Specification	Value
Diameter (Body)	2.36 in. (60 mm)
Diameter (Shaft)	8 mm with 2 mm keyway
Encoder Counts/Rev	42
Free Current	1.8 Amps
Free Speed	5676 RPM
Length (Body)	2.3 in. (58.25 mm)
Length (Shaft)	1.38 in. (35 mm)
Manufacturer Part #	REV-21-1650
Maximum Power	406 Watts
Motor Kv	473 Kv
Mounting Geometry	Four 10-32 holes on a 2 in. circle
Stall Current	105 Amps
Stall Torque	2.6 Nm
Voltage	12V DC
Weight	0.938 lbs

Appendix E – DVP&R

Table 3. Design Verification Plan for testing our verification prototype.

Planned Test	What it will test	Required resources
Mass Verification	Ensure that the mass falls within specification limit. [Spec 1]	Scale
System Dimensions	Ensure system is within size specification limits [Spec 2]	Meter Stick
Time to Replace Any Part	How long it takes to exchange a part on the rover [Spec 3]	Hand Tools, Stopwatch
Chassis Deflection	Deflection of Aluminum Extrusions under maximum load. [Spec 4]	Weights, Ruler/Caliper
Suspension Spring Deflection	Spring deflection/extension under various loading conditions [Stability of suspension]	Weights, Ruler/Caliper

Appendix F – Test Procedures

Test Name: System Weight

Purpose: Ensure total system weight meets competition requirements

Scope: Complete System

Equipment:

- Scale
- Calibration Weight

Hazards:

Safety Concern	Mitigation Method
Heavy lift items	<ul style="list-style-type: none">• 1 person lift: < 50lbs• 2-person lift: > 50 lbs

PPE Requirements:

- Closed Toed Shoes
- Long Pants

Facility: Mustang 60

Procedure:

1. Zero the scale
2. Place the calibration weight on the scale and note any error
3. Two people lift the rover onto the scale and note weight

Results: Pass if system weight less than or equal to 35kg

Test Date(s): 11/19/2024

Test Results:

Subsystem	Weight (kg)		Pass/Fail
	Estimated	Actual	
Differential	11.87	12.2	Pass
Chassis	1.83	1.97	Pass
Suspension	15.94	N/A	N/A
	TOTAL	14.17	Pass

NOTE: Suspension was not weighed since components are made from wood instead of aluminum. The differential and chassis have an actual total mass of 14.17 kg leaving a budget of 20.83 kg for the suspension, which is reasonable considering the estimated mass was 15.94.

Performed By: All

Test Name: System Dimensions

Purpose: Ensure the system does not exceed dimensional requirements of competition

Scope: Complete system

Equipment:

- Tape measure

Hazards: None

PPE Requirements:

- Close toed shoes
- Long pants

Facility: Mustang 60

Procedure:

1. Extend the tape measure to 1.2m
2. Measure the rover in 3 primary axes.

Results: Pass if no axis exceeds 1.2m

Test Date(s): 10/31/2024

Test Results:

Axis	Length (m)	Uncertainty (m)	Pass/Fail
1	1.1900	0.0005	Pass
2	0.8423	0.0005	Pass
3	0.7156	0.0005	Pass



Figure 12: Measuring the primary axes of the entire rover.

Test Name: Time to Replace Parts

Purpose: The purpose of the test is to test the modularity of our components in the rover, which is one of the main objectives. We will time ourselves on replacing any single part.

Scope: The test is for the entire rover.

Equipment:

- Allen wrench set
- Ratcheting Tool Set

Hazards:

- Pinching
- Weight Crushing

PPE Requirements: (e.g. safety goggles, respirators)

- safety gloves
- safety shoes
- attentive team members.

Facility: Bonderson Center (Shop)

Procedure:

- 1) Place the rover on flat ground and set the timer.
- 2) Use the Allen Wrench Set or Ratcheting Tool to remove a component
- 3) Replace it with a new component and time yourself.

Results:

Pass Criteria – Replace any components in 10 min.

Fail Criteria – Over the time limit.

Number of Sample to test

- Side Panels
- Differential Hardwares
- Wheel attachments
- Suspension Hardwares.

The Uncertainty Analysis will be done by looking up the uncertainty from our timer.

Test Date(s): 10/31/2024

Test Results:

Component	Time (min)	Uncertainty (s)	Pass/Fail
Suspension Hardware	10	0.5	Pass
Differential Hardwares	9	0.5	Pass
Panels	7	0.5	Pass
Wheel attachments	9	0.5	Pass



Figure 13: Two members of the group replacing the suspension components while timing themselves.

Comments: We noticed that replacing the suspension hardware takes the most time compared to the rest, due to its greater number of components.

Test Name: Chassis Deflection

Purpose: Determine chassis rigidity and structural integrity under shock loads

Scope: Chassis frame

Equipment:

- Assorted weights
- Bucket with hook
- Caliper
- Ruler
- Safety Glasses

Hazards:

Safety Concern	Mitigation Method
Heavy lift items	<ul style="list-style-type: none"> • 1 person lift: < 50 lbs.

	<ul style="list-style-type: none"> • 2-person lift: > 50 lbs.
Weight crush in case of failure	Ensure that when placing weights into bucket that feet and any other appendages are kept from under loading area.

PPE Requirements:

- Safety Glasses
- Closed-toe shoes

Facility:

- Mustang shop

Procedure:

1. Affix chassis frame to test stand
2. Record initial distance of frame to floor using ruler
3. Place bucket with hook in middle of chassis
4. Load weights until maximum shock load weight is achieved
5. Use ruler to record distance to floor under load
6. Remove weight and bucket
7. Perform test on all chassis frame areas and record requisite data

Test Date(s): 10/29/2024

Test Results:

Deflection Area	Deflection (cm)	Uncertainty (cm)	Pass/Fail
Side 1: 30 kg < 1cm	0.65	0.05	Pass
Side 2: 30 kg < 1cm	0.60	0.05	Pass
Front: 25 kg < 0.5 cm	0.30	0.05	Pass
Back: 25 kg < 0.5 cm	0.25	0.05	Pass



Figure 14: Two members measuring chassis deflection of Side 1.

Test Name: Suspension Spring Deflection

Purpose: To determine spring deflection/extension under various loading conditions and ensure that suspension assembly does not bow outward.

Scope: Suspension subassembly

Equipment:

- Assorted weights
- Bucket with hook
- Caliper
- Ruler
- Safety Glasses

Hazards:

Safety Concern	Mitigation Method
Heavy lift items	<ul style="list-style-type: none">• 1 person lift: < 50lbs• 2 person lift: > 50 lbs
Weight crush in case of failure	Ensure that when placing weights into bucket that feet and any other appendages are kept from under loading area.

PPE Requirements:

- Safety glasses
- Closed-toed shoes

Facility: Bonderson Courtyard

Procedure:

1. Affix rover to test stand
2. Record initial spring length with no load added to rover
3. Place bucket with hook in middle of chassis
4. Load weight
5. Use ruler/calipers to record spring extension
6. Record pass/fail
7. Remove weight and bucket
8. Repeat steps 2-7 for each loading condition

Results:

Test three loading conditions (10 kg, 20 kg, and 30 kg)

Record spring deflection

Pass: Spring does not exceed deflection of 254 mm and suspension does not bow out

Fail: Spring exceeds deflection of 254 mm and/or suspension bows out

Test Date(s): 11/12/2024

Test Results:

Loading Condition [kg]	Spring Length [mm]		Spring Deflection [mm]	Pass/Fail
	Initial (mm)	With Load		
10	120	125	5	Pass
20	120	132	12	Pass

Performed By: All