Project Notes:

Project Title: Autonomous Extrication Mechanism for Planetary Rovers on Loose Terrain
Name: Saanvi Singh

Note Well: There are NO SHORT-cuts to reading journal articles and taking notes from them. Comprehension is paramount. You will most likely need to read it several times, so set aside enough time in your schedule.

Knowledge Gaps:

This list provides a brief overview of the major knowledge gaps for this project, how they were resolved and where to find the information.

Knowledge Gap	Resolved By	Information is located	Date resolved
What are some methods that animals use to travel over rough terrain?	By doing a google search on animals that can travel over slopes and sandy terrain, then reading an article on dessert rattle snake and a research paper on the climbing mechanics of mountain goats	Lewinson, R. T., & Stefanyshyn, D. J. (2016). A descriptive analysis of the climbing mechanics of a mountain goat (Oreamnos americanus). *Zoology*, 119(6), 541–546. https://doi.org/10.1016/j.zool.2016.06.001	08/21/2025
What is the Martian terrain like?	Search for articles on this topic on Gordon Library's website.	Sheehan, W. (1970, January 1). *Geography of Mars, or areography*. SpringerLink. https://link.spri	09/03/2025

		nger.com/chapter/10.1007/978-3-319-09641-4_7#citeas	
What are some current methods being used by robots to traverse sandy terrain?	Found an article through Gordon library on a planetary rover that uses a crawling motion to overcome obstacles. And A literature review of robot design that are alread doing this.	Tomiło, P., (2025). MoonCrab: Design and tests of novel hybrid locomotion rover. *Results in Engineering*, 27, 106164. https://doi.org/10.1016/j.rineng.2025.106164 García, J. M., & Duarte, F. G. (2024). Mobile rolling robots designed to overcome obstacles: a review. *Forces in Mechanics*, 100283–100283. https://doi.org/10.1016/j.finmec.2024.100283	09/13/2025
What are grouser wheels?	By doing a google search on "what are grouser wheels" which led me to find articles on grouser shapes and parameters for rover grouser design.	Inotsume, H., Moreland, S., Skonieczny, K., & Wettergreen, D. (2019). Parametric study and design guidelines for	09/14/2025

		rigid wheels for planetary rovers. *Journal of Terramechanics, 85*, 39-57. https://doi.org/10.1016/j.jterra.2019.06.002 García, J. M., & Duarte, F. G. (2024). Mobile rolling robots designed to overcome obstacles: a review. *Forces in Mechanics*, 100283–100283. https://doi.org/10.1016/j.finmec.2024.100283	
What strategies are used to extract rovers when they are stuck?	"Command sequences for extrication of mars rovers"	https://www-robotics.jpl.nasa.gov/media/documents/rp_check_v4.pdf	10/16/2025

Literature Search Parameters:

These searches were performed between 08/20/2025 and XX/XX/2026.
List of keywords and databases used during this project.

Database/search engine	Keywords	Summary of search
Google	"Locomotion" and "Microgravity"	Found an article called "A Bio-Inspired Compliant Claw for Arboreal Locomotion in Micro-Gravity Environments" and started reading it on 08/20/2025
Google	"Animals that can traverse steep, sandy or rough terrain"	Found a list of animals such as mountain goats and Mojave rattle snakes, to learn about different methods of travelling over rough terrain and see how it can be incorporated into robots. Then I found and read an article called "Analysis of Climbing Mechanics of a Mountain Goat", to learn how mountain goats travel over steep terrain. Started reading article on 08/21/2025
Google	"Robots" and "Obstacle Avoidance"	Found and read a literature review article that provided an overview of 108 robots that used various different methods to overcome obstacles, on 09/06/2025
Gordon Library Website and Google	"Robots for Sandy Terrain"	Found a lot of articles on unique locomotion methods for traversing sandy terrain, such an article called "MoonCrab: Design and tests of novel hybrid locomotion rover". Read article on 09/13/2025.

Tags:

Tag Name	
Space Robotics	Biomimicry
Grousers	Locomotion Methods
Mars	Terrain
Extrication	

Article Notes: Template

Article notes should be on separate sheets

KEEP THIS BLANK AND USE AS A TEMPLATE

Source Title	
Source citation (APA Format)	
Original URL	
Source type	
Keywords	
#Tags	
Summary of key points + notes (include methodology)	
Research Question/Problem/ Need	
Important Figures	
VOCAB: (w/definition)	
Cited references to follow up on	
Follow up Questions	

Article #1 Notes: A Bio-Inspired Claw for Arboreal Locomotion in Micro-Gravity

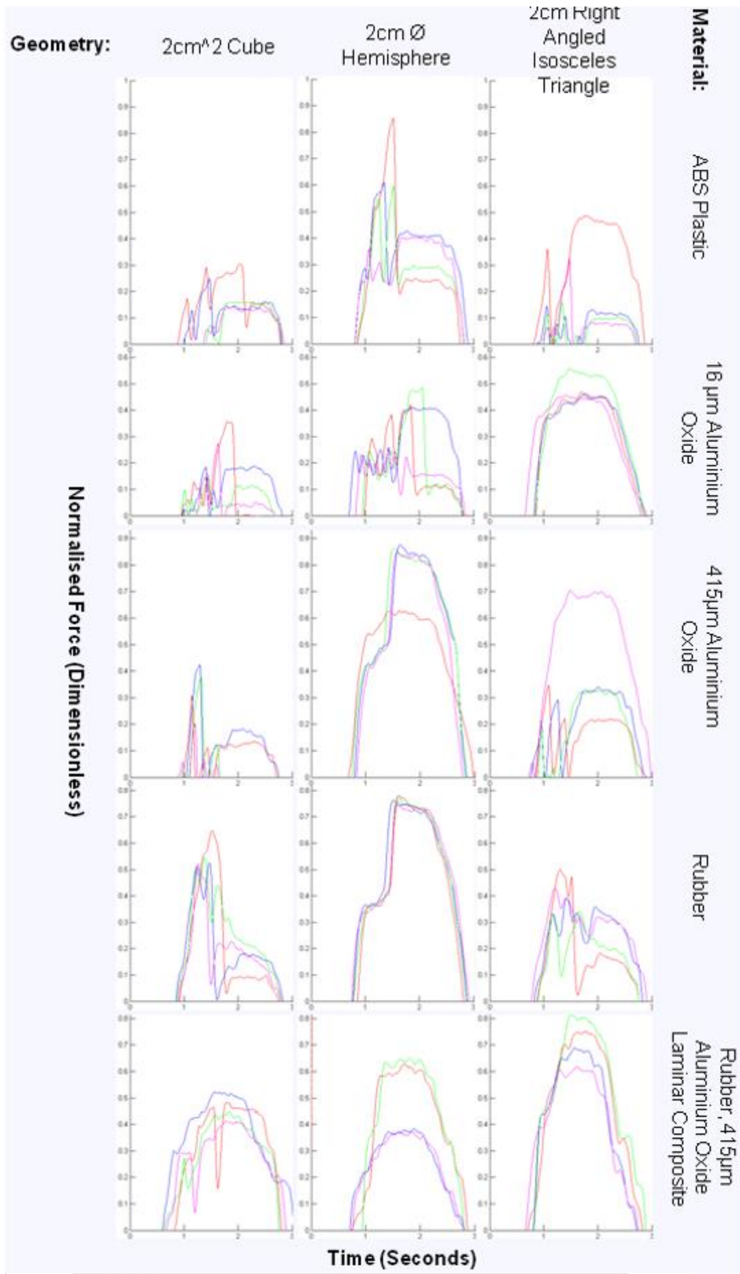
Source Title	Instiitute of Electrical and Electronics Engineers (IEEE)
Source citation (APA Format)	Matthew, R., Lund, H., & Yoshida, K., (2010). A bio-inspired compliant claw for arboreal locomotion in microgravity environments. *2010 IEEE/SICE International Symposium on System Integration (SII)*, 114–119. https://doi.org/10.1109/SII.2010.5708311
Original URL	A bio-inspired compliant claw for arboreal locomotion in microgravity environments | IEEE Conference Publication | IEEE Xplore
Source type	Scientific Journal
Keywords	Materials; Friction; Geometry; Robots; Force; Aluminum oxide; Surface roughness
#Tags	Space Robotics, Biomimicry

Summary of key points + notes (include methodology)	• There are two main types of end effectors, multi-purpose and specialized. Specialized manipulators are designed to carry out a single task efficiently while multi-purpose one's act as a general hand. **Claws could be used as a multi-purpose end effector.**
	• Arboreal animals use 3 main methods to climb around trees; claws, frictional grip, and adhesion.
	  o Claws are known for their curvature and tips that finish in a point. These points dig into the surface, allowing the animals to create a secure grip.
	  o Primates that use frictional grip, have thinner nails that are flat rather than pointed. They also use papillary ridges (fingerprints) to increase friction.
	  o Frictional grip method was used by animals that mostly reside on branches with smaller diameters.
	• It was decided that the surface of the claw would have a compliant design, it should deform to fit the target surface, since the surface would be rough with many niches. The “hand” was going to be subdivided into many separate “fingers”, and the fingers would be attached via an elastic spring allowing them to move independently (see Fig. 1.)
	• The claw has 3 fingers (the end tip section of the claw); each held in place with springs. As claw approaches the surface, the fingers and palm move together until contact is made. On contact, the palm continues to move while the fingers are stuck in place, causing the tips of the fingers to dig further into the target surface. (see Fig. 2. for

	finger design)
	• 4 main features are used to judge grip
	  o Overall maximum normalized force, which can be seen as the highest peak on a graph (Fig. 9.). This shows the maximum frictional force that can exist between two surfaces.
	  o After the maximum static friction has been surpassed, the end tip will slip. If the dynamic friction is lower than the static friction, control of the target could be lost once it starts to slip.
	  o Consistency is a key factor when deciding material as constant grip level are required for judging where to grasp target.
	  o Some materials exhibit a 'Catch' property, where after slipping their end tip was able to regain the grip.
	• Observed that a cubic tip had poor static and dynamic friction; hemispherical tips have high static friction and when combined with rubber and Al_2O_3 it exhibits 'catch'; angled tips have lower maximum normalized force but can achieve a higher force without catching the surface (see Fig. 5. for end tip shapes)
	• Materials wise, a composite of rubber and 415 micrometer Al_2O_3 showed good maximum static friction and provided the most consistent results.
	• **Rubber and 415 micrometer Al_2O_3 composite combined with an angled geometry showed the best grip characteristics, providing consistent grip without relying on catch and has a higher static and dynamic friction.**
	• The claw design can hold onto other surfaces in a similar way, regardless of how they contact the surface (Ex. Fig. 8.), since the overall structure can deform to fit the target material.
	• **Used a microgravity test rig to see if it will work in micro gravity.**
	• The idea is that a robot can use a pair of manipulators with this claw end-effector to traverse over a rough surface, by holding onto an anchor with arm, while reaching for the next with the other arm.
	
	Article Summary:
	Traditional wheeled robots aren't effective for movement in the microgravity environment of space. This research paper proposes an alternative robot design that uses robotic arms to anchor itself to an object and swing itself around that object, a form of movement known as brachiation. To come up with this design, three methods of gripping uneven surfaces were investigated – claws, frictional grip, and adhesion. Their final design is a robotic claw that uses springs allowing the claw to change its shape depending on the object it is trying to grip. It also uses triangular end tips with sandpaper on its end to increase the claw's grip on the object's surface. In the future, robots can use a pair of arms equipped with these claws to move across complex terrain.

Research Question/Problem/ Need	How can robots be maneuvered in micro gravity with the help of manipulators and robotic claws?

Important Figures



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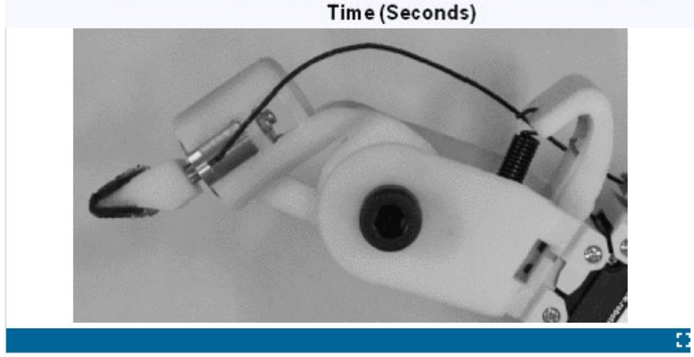

Fig. 6. 3 Axis force sensor and force sensor mount. The end tip can be changed with the test end-tips allowing the variation with geometry and material to me measured. The geometry of each end tip was chosen so that the point of contact would be the same for each test.

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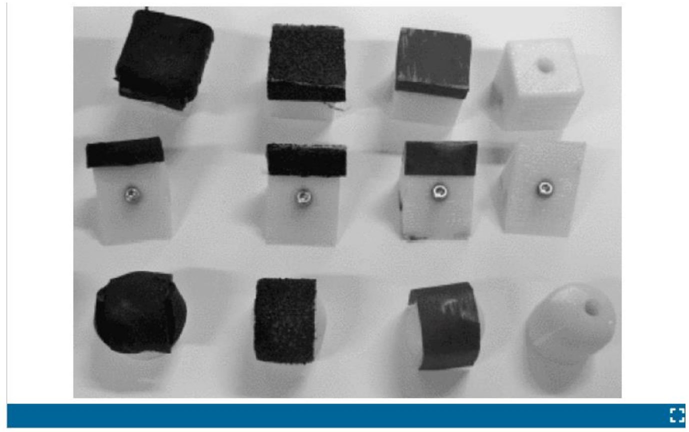
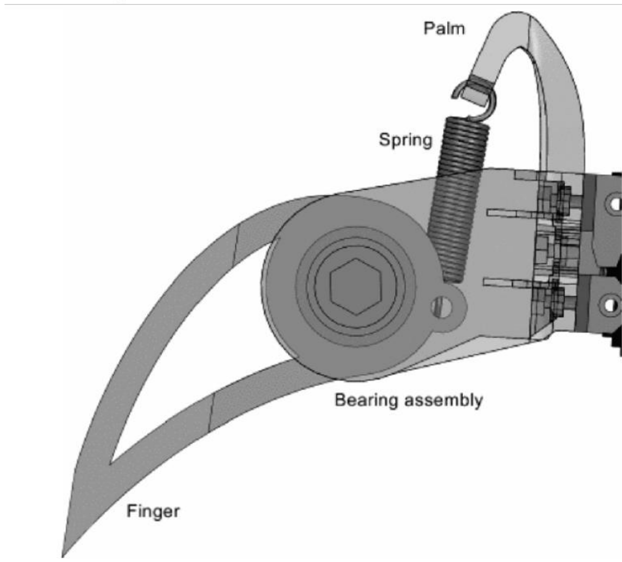
	 - **Fig. 5.** The full set of end-tips. Rows: Flat, angled and hemispherical geometries. Columns- Rubber, 415 and 16 micrometer Al_2O_3 and ABS plastic. Geometries are based on a 20mm by 20mm grid, with the hemisphere of radius 10mm, and angled tip being an isosceles triangle.  -
VOCAB: (w/definition)	• **Brachiation:** the movement of grasping objects and using them to swing from hold to hold • **Robotic Manipulators:** essentially robotic arms or multi-jointed appendages designed to perform precise and complex tasks in the environment of space • **Arboreal Animals:** animals that spend most of their lives dwelling in trees
Cited references to follow up on	• Oda, M., Nishida, M., & Nishida, S. (1996). Development of an eva end effector, grapple fixtures and tools for the satellite mounted robot system. *Intelligent Robots and Systems '96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on Intelligent Robots and Systems, 1996.* • Keymeulen, D., & Assad, C., (2001). Investigation of the harada robot hand for space. *IEEE RAS Internation Conference on Humanoid Robots University International Conference Center, Tokyo, Japan, 2001.*

Follow up Questions	• The article states that any damage to the tip of the claw will negatively affect its future performance. How can this be avoided? • The claw mechanism works well for any kind of rough surface, but can it be modified to also grip onto smooth surfaces? (probably using adhesion, can adhesion and this claw method be combined to make a claw?) • Does increasing the number of “fingers” in the claw increase its grip strength?

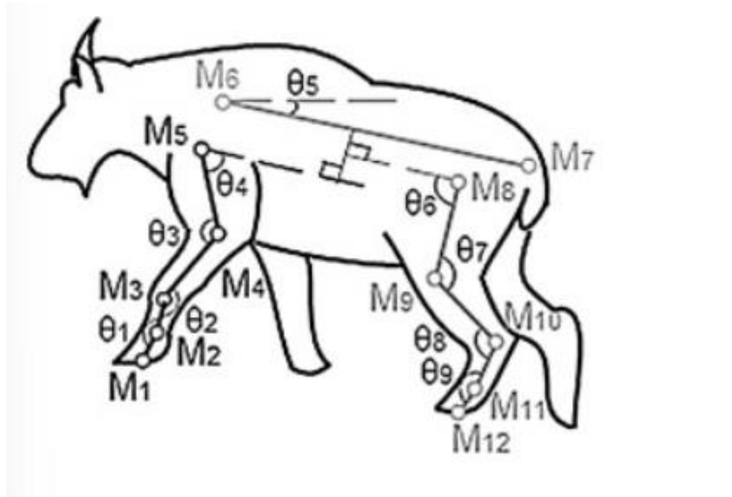
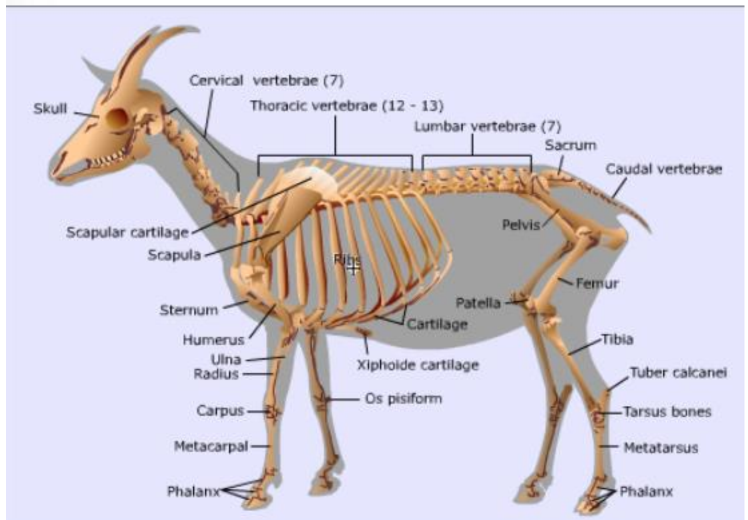
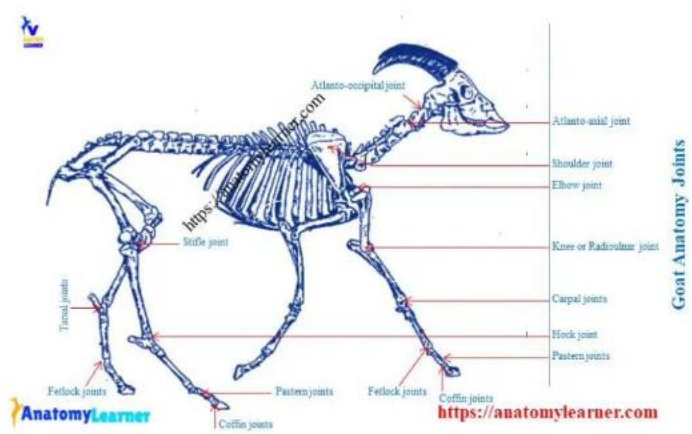
Article #2 Notes: Analysis of the Climbing Mechanics of a Mountain Goat

Source Title	Science Direct
Source citation (APA Format)	Lewinson, R. T., & Stefanyshyn, D. J., (2016). A descriptive analysis of the climbing mechanics of a mountain goat (Oreamnos americanus). *Zoology*, *119*(6), 541–546. https://doi.org/10.1016/j.zool.2016.06.001
Original URL	https://www.sciencedirect.com/science/article/pii/S0944200616300514
Source type	Scientific Journal
Keywords	Climbing Ability; Climbing Kinematics; Biomechanics; Mountain Ungulates; Incline
#Tags	Biomimicry

Summary of key points + notes (include methodology)	• **Note: there is a lot of possibility for error in this research because it was only done on one goat and in an uncontrolled environment.**
	• This study was a naturalistic observational study, so the mountain goat was studied in the wild.
	• The goat would push off the mountain with its hindlimbs, catch the mountain with its forelimbs, propel itself up the slope and repeat.
	    o Push-off - the phase where the hindlimbs were in contact with the slope
	    o Pull-up – the phase where the forelimb was in contact with the slope
	• See Fig. 2. for schematic diagram of goat's anatomy and joint markers/locations
	• Out of 9 frames of a video of the mountain goat climbing, the first 6 represented the push-off phase (when the goat extended its hindlimbs to propel its forearms forward), and the last 3 frames showed the pull-up phase of climbing (when hindlimb push-off is completed and the forelimbs were used to rapidly pull up the goat's body.
	• **Used Matlab to convert the video of the goat climbing to binary, with goat being represented with white and background as black. Matlab was also used to calculate the white area of the goat.**
	• Using MatLab the center of the white area was calculated for each frame. Assuming a constant density throughout the

body, the center of the area is also the COM.
  - Because the camera wasn't stationary, changes to the COM position were expressed relative to either the fore or rear limb (whichever was in contact with the ground)
  - Fig. 1. shows the details of the analysis process
- **Determining the scapula orientation in quadrupeds is challenging due to the lack of sophisticated equipment. Thus, the analysis doesn't account for the angular orientation of the scapula on the torso.**
  - It's likely that the changes to the scapulohumeral angle were relatively small, as is the case for other quadrupeds.
  - If there was an angular change of the scapulohumeral joint, it would be reflected in the angular change of the scapula and shoulder girdle itself.
- Torso angular velocities were determined by calculating the change in the angular position, then dividing it by the time difference between frames.
- The position of the instantaneous center of rotation of the torso was also calculated in MatLab by determining the linear velocity of the anterior torso marker (see Fig. 2. for marker location) and then dividing it by the torso angular velocity.
- The angle of the mountain slope was determined using trigonometry.
- All joint angle data can be found in Fig. 3.
- In the hindlimb, the metatarsophalangeal joint underwent a small amount of flexion, which occurred likely due to body weight and large ground reaction forces.
- A decrease in the distance between the scapulohumeral marker and anterior torso marker was observed due to a combination of scapulohumeral protraction (extending a part of the body) and elevation (movement of a body part upwards). These movements allowed the goat to propel its body towards the mountain & tuck in its forelimbs close to its torso.
  - Tucking the forelegs in (likely) allowed the goat to maintain its COM as close to the mountain face as possible.
  - Throughout the pull-up phase, the goat seemed to lock its humerus at a constant angle relative to its torso.
- The distance between the scapulohumeral and anterior torso marker increased during the duration of the pull-up phase (because the goat puts its leg up to pull itself?)
- Metacarpophalangeal joints experience minimal angular

	change but have a slight extension during the pull up phase. • The majority of angular motion in the forelimbs across the pull-up phase was found in the carpal and elbow joint, with slight joint extension. • During the push-off phase, the whole-body COM was found close to the elbow joint, allowing the elbow and carpal joints to extend. • During push-off phase, torso angular velocity went from –163 degree/s (rotating away from mountain, between frames 1 and 2) to 67.9 degrees/s (rotating towards the mountain, between frames 5 and 6) • Length of torso increased by about 11.3 cm throughout push-off phase. • During pull-up phase angular velocity of torso decreased from 79.4 to 59.4 degrees/sec (rotating towards the mountain) • Torso experienced angular acceleration towards the mountain face during the push-off phase and angular deceleration during pull-up phase. • A goat's ability to propel itself up a slope during the pull-up phase may explain why the mountain goat has such massive shoulder musculature with a prominent shoulder muscle hump. Article Summary: Mountain goats are animals that can very effectively climb mountains. While they're very famous for this ability, they have never been studied biomechanically, which was the goal of this research paper. A goat was found and recorded while climbing a 45-degree incline in its natural habitat. Then its climbing motion was studied by exporting pictures from the video into MatLab. The climbing motion of the mountain goat was divided into two parts, the push-off and pull-up phase. During the push-off phase, the goat extended its hindlimb to "push-off" the mountain face and tucked in its forelimb. In the pull-up phase, it brought its hindlegs close to its torso and extended its forelimbs in close proximity to the goat's center of mass. There is a lot of possibility of error in this research, due to the fact that only one goat was studied, and it was studied in an uncontrolled environment.
Research Question/Problem/ Need	How are mountain goats able to travel on rough and steep terrains?
Important Figures	

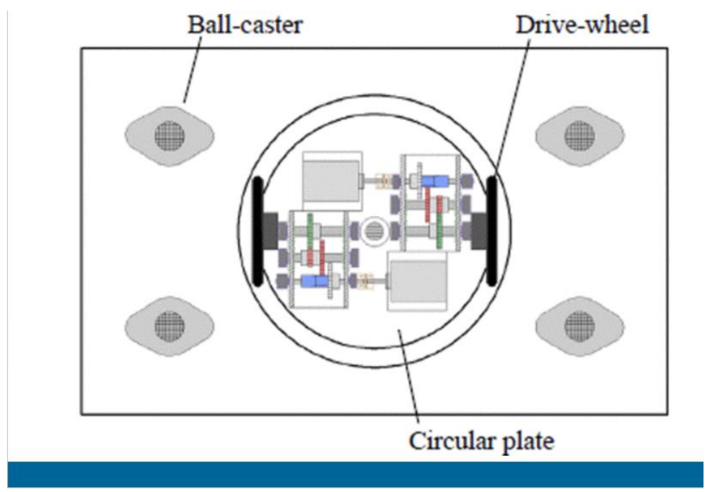
	 -  -  -
VOCAB: (w/definition)	• **COM:** center of mass. • **Naturalistic Observational Study:** Studying an animal in the wild, not under controlled conditions. • **Scapula:** Flat bones that connect the upper limb to the skeleton, allowing various types of movements.

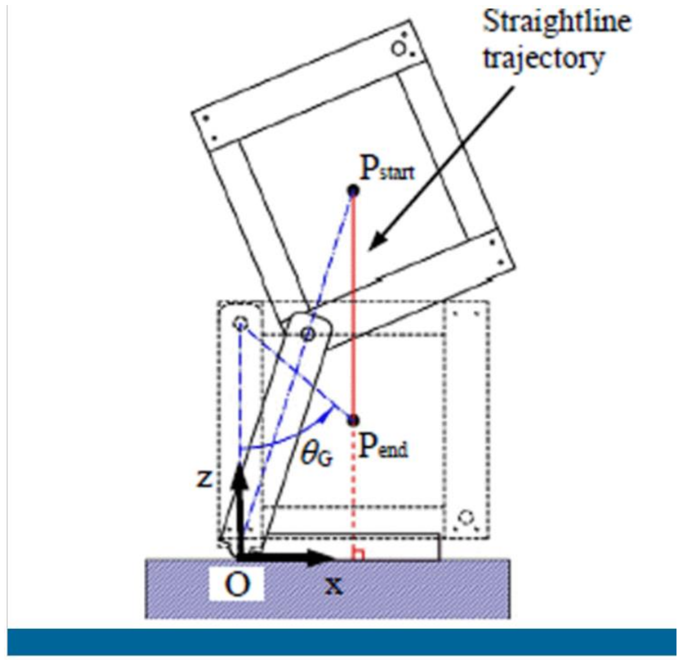
	• **Scapulohumeral Joint:** shoulder joint, the ball and socket joint between the scapula and the humerus (the long bone in the upper arm) • **Shoulder Girdle:** a bony structure that connects the upper arm to the axial skeleton; made up of two bones – the clavicle and the scapula • **Anterior Torso:** refers to the front part of the torso • **Flexion:** the condition of being bent, especially in limbs and joints.
Cited references to follow up on	• Arnold, A.S., Lee, D.V., Biewener, A.A., 2013. Modulation of joint moments and work in the goat hindlimb with locomotor speed and surface grade. *Journal of Experimental Biology*, 216, 2201–2212. https://doi.org/10.1016/j.zool.2016.06.001 • Fischer, M.S., Schilling, N., Schmidt, M., Haarhaus, D., Witte, H., 2002. Basic limb kinematics of small therian mammals. *Journal of Experimental Biology*, 205, 1315–1338. https://doi.org/10.1242/jeb.205.9.1315
Follow up Questions	• How can cheaper equipment be used to study the angular orientation of the scapula on the torso and how does it relate to the climbing mechanics of mountain goats? • How does the propulsive impulse in the hindlimbs generate and is it a major contributor to the push-off phase in climbing? • Has the climbing mechanism of mountain goats been incorporated into robots to allow robots to traverse slopes and steep terrain?

Article #3 Notes: Design of Translational Locomotion Mechanism for Stair-Cleaning Robot

Source Title	Insititute of Electrical and Electronics Engineers (IEEE)
Source citation (APA Format)	Kakudou, T., Watanabe, K., & Nagai, I., (2011). Study on mobile mechanism for a stair cleaning robot - Design of translational locomotion mechanism. *11th International Conference on Control, Automation and Systems*, Gyeonggi-do, Korea (South), 1213-1216.
Original URL	[Study on mobile mechanism for a stair cleaning robot - Design of translational locomotion mechanism | IEEE Conference Publication | IEEE Xplore]
Source type	Scientific Journal
Keywords	Cleaning Robot; Stairs; Mobile mechanism
#Tags	Locomotion Methods

Summary of key points + notes (include methodology)	• The purpose of the cleaning robot is to automate cleaning in a 3-dimensional space, by rotating two L-shaped legs to climb up and down stairs.
	• See Fig. 3. to see how robots will go up and down stairs.
	• The center of Gravity is set to the center of the robot's body.
	• **When rotating the robot's body, there is a possibility that it falls by its centrifugal force**
	    o This effect can be decreased by making the center of gravity of the robot follow a straight line (see Fig. 4.).
	• Robot is controlled using a PID controller to move the CG of the robot to the point P start to the point P end.
	• Robot might have difficulty with its corners colliding with walls due to its rectangular shape.
	    o This is solved using omni-directional wheels to give the robot omnidirectional mobility
	• Since the robot climbs downstairs by rotating its body, its upper and lower sides might be reversed, so two mechanisms of moving are attached to the top and bottom of the robot.
	• To reduce robot weight, it's wise to use the fewest possible actuators.
	• The study robot used an omni-directional mobile mechanism of two-wheel-drive system.
	• The locomotive mechanism is attached to the top and bottom of the robot body.
	• 4 basic types of locomotion for commonly marketed cleaning

	robots - o Parallel Motion: repeated motion, combining advanced 90 degree turns, basically goes down row by row until you get where you want to go. o Spiral Motion: Ex Wallpapers, motion of moving outwards on a spiral path. o Wall-reflection Motion – changing direction at random when you have an obstacle. Article Summary: Robots are starting to be used as an alternative method to clean human living environments, rather than having people dedicated for this job. This robot design proposed in this article will be able to travel up and down stairs to autonomously clean multiple levels of a house. The robot is equipped with two "L" shaped legs that allow the robot to move up and down stairs by rotating its entire body. This paper just covers the conceptualization of such a robot and mentions plans of building a prototype for this design in the future.
Research Question/Problem/ Need	Need: To save labor and energy required to clean 3 dimensional buildings, by building a robot that can also clean up the stairs.
Important Figures	 - Fig. 5 Mechanism for translational movement

	-  **Fig. 4** Straight line trajectory for posture control
VOCAB: (w/definition)	• **Translational locomotion:** refers to a type of movement of an object, where every point of the object moves the same amount of distance in a given amount of time.
Cited references to follow up on	• Tribelhoron, B. & Dodds, Z., (2007). Evaluating the Roomba: A Low-cost, Ubiquitous Platform for Robotics Research and Educations. *Proceedings 2007 of the IEEE International Conference on Robotics and Automation*, pp. 1393-1399.
Follow up Questions	• Can we modify this robot's design, so that it can be used on natural disaster sites? Ex. rolling robot that tumbles over difficult terrain? • Can we combine this with claw mechanism in article #2? • What modification will need to be made to enable the robot to move up the stairs as well?

Article #4 Notes: MoonCrab: Design and Tests of a Novel Hybrid Locomotion Rover

Source Title	Science Direct
Source citation (APA Format)	Tomiło, P., (2025). MoonCrab: Design and tests of novel hybrid locomotion rover. *Results in Engineering*, *27*, 106164. https://doi.org/10.1016/j.rineng.2025.106164
Original URL	MoonCrab: Design and tests of novel hybrid locomotion rover - ScienceDirect
Source type	Scientific Journal
Keywords	Hybrid locomotion; Planetary Rover; Slope Climbing; Crawling Mechanism
#Tags	Locomotion Methods

Summary of key points + notes (include methodology)	• Wheeled rover have low production costs due to their simpler designs (making them more appealing to space agencies)
	• Walking Rovers, offer more mobility and flexibility allowing to travel into hard-to-reach regions.
	• More degrees of freedom = more complexity
	• Active mechanisms allow for more adaptability to terrain
	• The Moon Crab design can use wheels the traditional way, adjust suspension depending on the terrain, and use limbs for crawling (check pg 3 for more details)
	• The grouser wheels used on the Moon Crab have ribs curved opposite to the rover's direction of travel, increasing its traction with the ground because it increased the effective contact area between grouser and ground (similar to the positioning of oars while kayaking)
	    ○ This helps with better thrust transfer, reduced slippage, and reduced wheel sinking in soft ground
	• Anchor blades (the ribs of the grouser wheels?) are designed to have the largest possible surface contact with the ground,
	    ○ Allows for more effective dispersion of shear forces to granular ground, improving anchoring ability
	• **Roughness of 3D printed parts can increase effectiveness of structure's interaction with the ground.**
	• **Servos that send information about acceleration, velocity, torque etc. could also be used in testing.**
	• When robot was tested on a slope at an angle, its efficiency is calculated using Dr = Di/Do

	◦ Di = avg distance travelled for a slope angle of i degrees ◦ Do = avg distance traveled for a slope angle of 0 degrees ◦ Dr = locomotion efficiency • Granular Material used to test: ◦ Quartz sand of 0.5 - 1 mm ▪ High permeability ▪ Cohesionless (lacks strong bonds between particles, relies on friction to maintain these bonds, Ex. loose sand) ▪ Similar to Alluvial formations (areas of loose sands deposited by water) ◦ Quartz sand of 0.1 - 0.5 mm ▪ Increased degree of compactability ▪ Similar to surfaces with dusty characteristic ◦ Mixture of quartz sand (0.5-1mm), basalt dust and kaolinite, with weight ratio of 5:4:1 ▪ Similar to Martian regolith in terms of grain size • Test Stand (the container/area where the robot will be tested: ◦ Test Stand set up on a hydraulic jack, so that the slope angle could be changed until the robot lost its ability to move ◦ Use localization system with IR light to determine rover's position • Results: ◦ At and incline of more than 25 degrees, a complete loss of locomotion was observed due to sinking ◦ Crawling mechanism had higher stability and adaptability under limited traction condition ◦ The higher the slope, the lower the performance for both modes of locomotion ▪ However, in the crawling mechanism the decrease in efficiency at higher slope angles is much smaller ▪ Decrease in efficiency started at slope inclinations higher than 15 degrees (changes based on materials). ▪ Maximum slope at which the rover could stay efficient was 28 degrees ▪ At a 15-degree incline, the anchor blades were able to better anchor themselves in the sand ◦ **Linear regression was used a lot during testing (figure out what it is an why it is helpful)** ◦ **Crawling mechanism was clearly more efficient and traversing increasingly sloped terrain than compared to traditional wheel systems and is also adaptable on rough terrain** • Conclusion: ◦ Crawling System is way better on slopes than wheels

- Could prove to be an effective solution for areas with variable terrain
- More adaptable to terrain like loose sand or unstable soil
- Doesn't express sinking of wheels in the ground, unlike with traditional wheeled movement
- Limitations of crawling mechanism include:
  - A single climbing cycle has a duration longer than compared to traditional rovers covering the same distance (could affect operations where speed is crucial)
  - Climbing mechanism is more complex and consumes more energy
  - Testing was conducted without compensating for Mars's low gravity

Article Summary:
The exploration of other planets is crucial to understanding our own, and planetary rovers capable of navigating more complex terrain are required in order to successfully explore these planets. This paper describes the design, prototyping and testing process for an alternative rover with a crawling mechanism. The locomotion performance and crawling mechanism of the rover was experimentally compared against the traditional wheeled rovers. The MoonCrab was tested on quartz soil (coarse sand), finer quartz sand, and a mixture of quartz sand, basalt dust and kaolinite. The results show that the crawling mechanism can better traverse steeper slopes. It is also more adaptable and stable when compared to a traditional wheeled rover. Next steps include testing the rover on other types of terrain and using simulations to train the rover to automatically respond to obstacles.

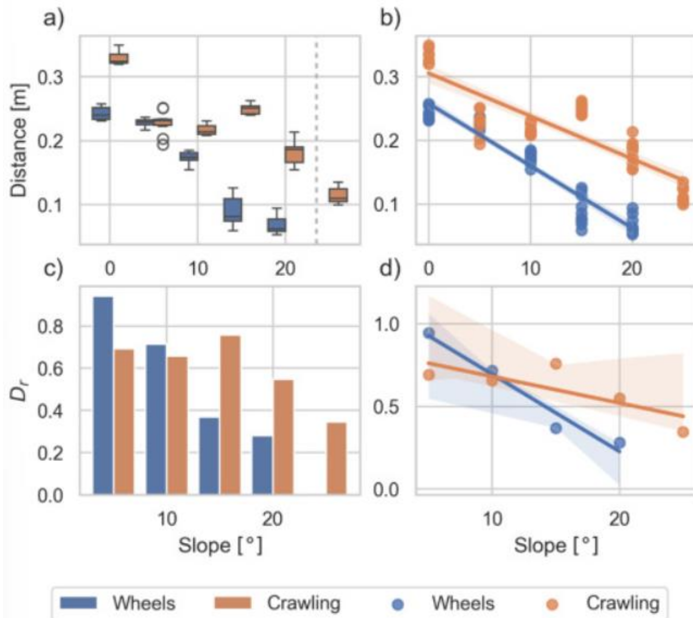
Research Question/Problem/ Need

Can a hybrid crawling and driving robot efficiently traverse rough terrain and slopes of various inclines?

Important Figures

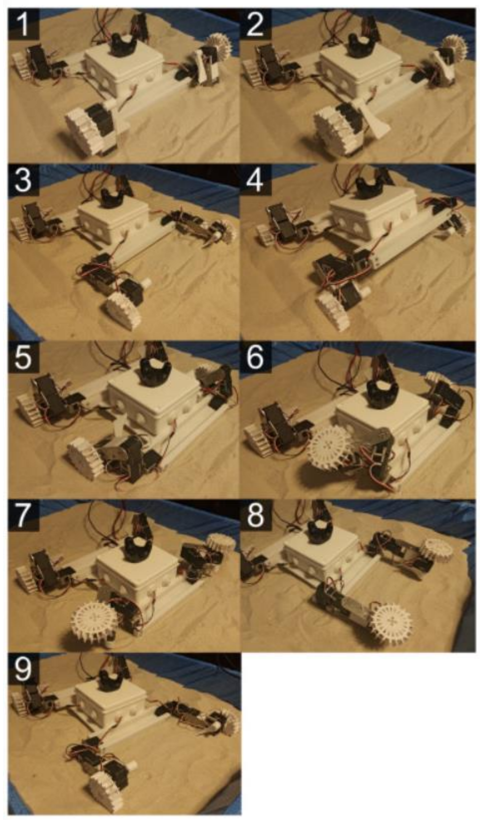
Table 8. Statistical analysis for the crawling mechanism (quartz sand 0.5–1.0 mm).

Slope	mean	std	min	25 %	Median	75 %	Max
[°]	[m]						
0	0.2978	0.0127	0.2802	0.2891	0.2975	0.3048	0.3219
5	0.2974	0.0066	0.2907	0.2931	0.2949	0.3016	0.3095
10	0.2473	0.0163	0.2227	0.2340	0.2498	0.2578	0.2674
15	0.2352	0.0148	0.2167	0.2234	0.2340	0.2496	0.2549
20	0.2152	0.0086	0.2055	0.2092	0.2122	0.2230	0.2290
25	0.1774	0.0053	0.1708	0.1724	0.1777	0.1822	0.1850
28	0.1364	0.0080	0.1291	0.1300	0.1315	0.1443	0.1473



a)
b)
c)
d)
Distance [m]
D_r
Slope [°]
Slope [°]
Wheels
Crawling
Wheels
Crawling

-



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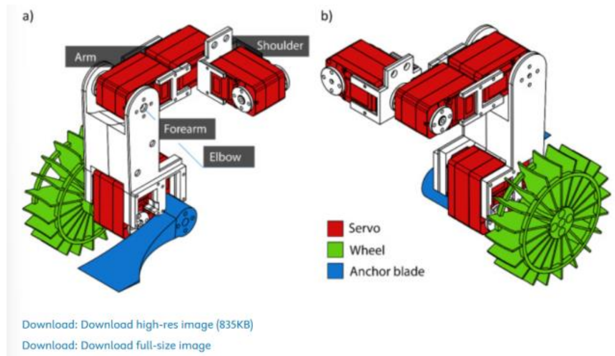
	- 
VOCAB: (w/definition)	• **Mounted axially**: mounting method where components are secured in place by bolts that run perpendicular to the disc (provides high stability and multidirectional mobility) • **Lateral Motion**: sideways motion • **Longitudinal Motion**: motion along the long axis • **Grouser Wheels:** devices intended to increase the traction of continuous tracks; wheel equipped with convex ribs (grousers) • **Torque:** the twisting force that tends to cause rotation • **Shear Forces:** Internal forces acting parallel to a surface, attempting to slide or deform one part of the surface to another. • **Permeability:** ability of a material to allow fluid to pass through it • **Degree of Compactability:** Percentage decrease in height of loosely packed sand when a certain amount of pressure is applied
Cited references to follow up on	• Audouard, J., Poulet, F., Vincendon, M., Milliken, R. E., Jouglet, D., Bibring, J.-P., Gondet, B., & Langevin, Y., (2014). Water in the Martian regolith from OMEGA/Mars Express. *Journal of Geophysical Research: Planets,* 119(8), 1969-1989. https://doi.org/10.1002/2014JE004649 • Fujiwara, D., et al. (2025). Climbing loose surfaces with steep slopes using a small push-rolling rover. *Journal of Terramechanics,* 118, 101043. https://doi.org/10.1016/j.jterra.2024.XXXXXX
Follow up Questions	• How can these walking and wheeled rovers be combined to preserve their strengths (paper already does this but how can this be improved)? (check Fig 1, 2, & 3) o Ex. inching mechanism (push and roll) o Adaptive change of wheelbase o Sidewinding (use combined leg-wheel mechanism) o Robot with limbs that end with wheels • Look into the terrain adaptive wheel-legged robot for simple but efficient design. • Grouser wheels enable robots to generate traction in the forward motion, but does it prevent the robot from going backward

	efficiently? • How can the crawling mechanism be sped up for situations where speed is key?

Article #5 Notes: Geography of Mars, or Areography

Source Title	Camille Flammarion's The Planet Mars
Source citation (APA Format)	Sheehan, W., (1970, January 1). *Geography of Mars, or areography*. SpringerLink. https://link.springer.com/chapter/10.1007/978-3-319-09641-4_7#citeas
Original URL	Geography of Mars, or Areography | SpringerLink
Source type	Textbook
Keywords	Dark Patch; Bright Patch; Wide Land; White Border; Martian Orbit
#Tags	Mars

Summary of key points + notes (include methodology)	• Regions of the planet in general are divided into two subcategories, bright countries and dark regions. **Bright countries** ordinarily have a color that is dark yellow or orange, sometimes shades of yellow or pure white. **Dark regions** are mostly iron-grey with a green tint, in all gradations from black to ashy grey.
	    o Various regions show changes of tint in some regions of Mars
	• Mars' surface is constantly changing
	• Dark and bright patches can be permanent or constantly changing (maybe due to observational issues, or because of geological activities on mars)
	    o The Martian surface contains liquids, and it is believed that liquids areas are darker because water and liquids in general absorb more light than continental surfaces.
	    o Each year we see the melting of Martian Snows, and this process produces a dark border around the polar cap.
	    o Changes in tone are frequently observed in dark patches which indicate a liquid element rather than solid ground.
	• **We therefore assume that brighter regions are continents and darker regions are seas.**
	• The area of land is only slightly greater than the area of seas (check important figures section for more details)

	• Mars is an eternally arid desert, with the water and sunlight on the planet playing opposite roles than they do on earth. • The coloration of continents could be due to vegetal covering formed on its surface. o Its coloration has already been compared with field of wheat from the vantage of an air balloon. o Colorations vary from one land to another, and even over the same regions over the span of a couple of years. o Vegetation can be reddish, e.x. lycopods, a plant with a Martian reddish-yellow color. o Chlorophyll on Earth is made up of two elements, one green and one yellow, so it is possible that in reddish plants the yellow pigment exists alone or dominant. • 77,000,000 square km of land and 66,000,000 square km of water on Mars. • According to calculations by Helmholtz (look at pg 440) Mars' heat condensation should be only 1,795 degrees, therefore it should have long since become cold at its center. We also know that the internal heat of Earth has no effect on our surface temperature or vegetation/animal life. • Chains of mountains are rare, although there may be some peaks, shown by whitish patches • On the right-hand coasts of the Hourglass Sea and up to Herschel Strait there seems to be cliffs rather than beaches, because the extensions of the sea always occur at the left-hand coast. • The northern hemisphere of mars is higher than the southern hemisphere. • The seas seem to be mainly in the South, maybe because of the Sun's attraction to the Martian terrestrial hemispheres which are closest to the Sun during the half period of the revolution. Article Summary: Mars' terrain is very diverse and complex for robotic rovers to traverse. The Red Planet's is divided into two regions, dark regions and light regions. Darker regions are assumed to be the sea while lighter regions are the sand. Martian terrain also includes hilly areas, and the colors of the sand can indicate the types of chemicals present in the soil.
Research Question/Problem/ Need	To provide an overview of dark and bright patches on the geography of Mars.
Important Figures	- Textbook chapter did not include any pictures, however satellite pictures of the dark and bright patches on Mars

	described in this chapter would have helped add context to the information.
VOCAB: (w/definition)	• **Sombre Patches:** A.k.a. Recuring Slope Lineae are dark streaks that appear on the Martian surface
Cited references to follow up on	• Textbook chapter did not provide any extra references
Follow up Questions	• Can a computer program be created to identify bright and dark patches easily? • Is there a better way to classify the regions of Mars than dark and bright, since dark and bright regions tend to change? • How can observational issues when identifying and you have never leaned room bright regions be detected?

Article #6 Notes: Mobile Rolling Robots Designed to Overcome Obstacles: A review

Source Title	ScienceDirect.com
Source citation (APA Format)	García, J. M., & Duarte, F. G. (2024). Mobile rolling robots designed to overcome obstacles: a review. *Forces in Mechanics*, 100283–100283. https://doi.org/10.1016/j.finmec.2024.100283
Original URL	Mobile rolling robots designed to overcome obstacles: A review - ScienceDirect
Source type	Science Journal
Keywords	Mobile robots with rolling; Obstacle overcoming; Stair climbing; Navigability; Tip-over stability; Motion control
#Tags	Locomotion Methods
Summary of key points + notes (include methodology)	• 3 common locomotion systems used in ground mobile robots ◦ 1. Wheel traction, allows the robot to move quickly and efficiently when navigating on hard and rigid surfaces ▪ Efficiency decreases when encountering granular materials (like sand) and obstacles higher than the wheel's radius ◦ 2. Track traction, improves robot's grip on the ground, making it more efficient on terrain with loose particles ▪ However, this type of traction consumes a significant amount of energy, which is a valuable resource especially since energy for robots is often limited. ◦ 3. Robots with legs, allowing them to overcome almost any type of obstacle, but with a lower forward speed. ▪ They also require more complex mechanical and control systems • **A robot's ability to overcome obstacles relies heavily on the robot's ability to contact the obstacle's upper edge.** • This paper mostly focuses on wheeled robots • Robots with Suspension Systems: ◦ They essentially isolate the robot from terrain irregularities and regulate vertical movement of the wheel

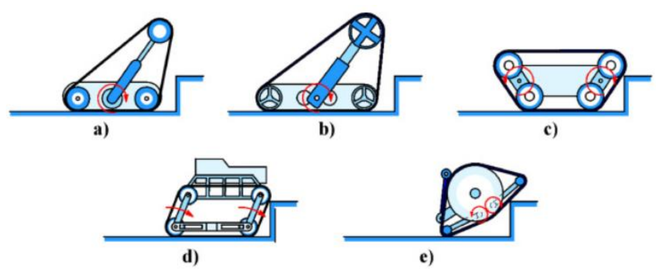
	○ Passive Suspension Systems: type of suspension with predefined parameters that aren't adjustable automatically. Within this system there are 2 commonly used systems: ▪ Spring – Damper: They store energy through springs and dissipate it through dampers (a.k.a. shock absorbers). The mechanism in fig 2a allows the robot to adjust the height of its wheels allowing it to overcome larger obstacles. This combined with body articulation enables robots to adapt to uneven terrains. ▪ Rocker Bogie and Linkage Mechanisms: Passive mechanisms and wheels without the presence of dampers or springs. The Rocker, connected to the chassis through a rotational joint, links to the opposite Rocker, causing one to move in the opposite direction as the other. Ex if front left wheel goes up, the front right wheel is pushed down the same amount of distance. The Bogie has two wheels that rotate freely, around a pivot point connected to the Rocker. This ensures both of its wheels always seek contact with the ground. This mechanism is used in many NASA rovers. ○ Active Suspension: Suspension that stores, dissipates and introduces energy into the system through actuators. Their operation is regulated by sensors and controllers. ▪ Spring-Damper-Actuators: typical spring-damper system is coupled with an actuator, which adds an additional force to the wheels ensuring they always stay in contact with the ground, balancing the height of all 6 wheels to maintain the robot's tilt, and even lifting a wheel when it stuck. ▪ Linkage and Actuator Mechanisms: In a suspension system primarily composed of linkages, actuators are attached to change their position as required. • Robots with single propulsion systems: ○ Wheeled Robots: Efficient on hard terrain but lacking on uneven or obstacle ridden surfaces. Some innovative ways to increase wheels radius and maximum obstacle height to overcome. ▪ Wheels on Rotational Structures: Wheels assembled concentrically on a rotational

structure that moves the wheels in a circular motion with a radius larger than the wheel's radius. It has 2 Degrees of Freedom (DOFs): structure to rotate and to provide traction to the wheels (Fig 6a). A variation of this design can also have only 1 DOF.

- Wheels with Appendages (a.k.a. segmented wheels): These wheels are bio inspired, designed by looking at the leg of insects. These wheels lack a perimeter edge and instead feature a circular base that rotates around an axis, which allows the robot to overcome obstacles bigger than itself. However, they are less stable and maneuverable than traditional wheeled robots. In the 6 wheeled Wheg 1 robot, the appendages are configured so that 3 appendages touch the ground simultaneously. (2 on one side, 1 on the other). Robot in (Fig 7e) uses a wheel composed of 3 rods which makes 6 spokes. The length of these spokes is variable allowing them to adapt to rough terrain. Segmented wheels can also be used to overcome obstacles by hooking onto them with their straight edge.
- Transformable Wheels: Wheels that can transform to have a more effective radius than their original, allowing them to overcome taller obstacles. Ex Fig 8a robot can transform its wheel into legs. 2 DOFs – increase in radius and other for leg reorientation and driving. In Fig 8d rollers have been installed on the legs to make the wheels omnidirectional before deploying legs. **Bar Mechanisms are** used to transform the wheels. Wheels that turn into 3 legs are done with one motor and **triradial link**. Legs can also be held in closed position with the use of magnets.
- Wheels on Tiltable Structures: This feature was shown in the VmaxCarrier2 robot, which consists of 2 discs surrounded by non-steerable wheels. These discs have the ability to be tilted using pneumatic actuators, allowing robots to overcome obstacles with a height greater than the wheel radius.

	▪ Wheels with additional support linkages: These have additional linkages (or legs) connected to the outer perimeter of the wheels, that can extend out and lift the wheel to a greater height, allowing it to reach the top of an obstacle. o Robots with Tracks: Use of tracks allows robots to increase their traction on uneven terrain or loose particles, but results in a higher energy consumption due to the friction involved. In standard tracked robots the maximum height of the obstacle that can be overcome is equal to the radius of the wheel to which the track is attached, but this can be changed with some modifications. ▪ Pair of enhanced tracks: The front wheel of the truck can be replaced with 2 wheels, where they are arranged in such a way that the track is now sloping in the front, allowing it to contact the upper edge of obstacles. This can also be modified so that the chassis of the robot is rotated upward by the driving wheel, allowing the chassis to touch the top of the obstacle. ▪ Multiple Tracks: includes robots that have more than one pair of tracks that can be arranged in a variety of configurations depending on the obstacle. This can be used by the robot to lift to one set of tracks (the smaller one) to touch the upper edge of an obstacle. ▪ Reconfigurable Tracks: Robots with tracks that can change shape and dimension. Ex robots with an extendable arm that rotates around the center of the chassis, changing the shape of the track and allowing for different angles of attack (Fig 12). Two such arms with 1 DOF each allow the robot to have 2 different angles of attack. o Robots with Legs: Can better navigate certain obstacles but have complicated control systems, design and implementation. o Robots with multiple locomotion systems: (a.k.a. Hybrid Robots) ▪ Rolling/Walking: Usually consist of legs with wheels on their ends. To overcome obstacles, the robot bends its leg forward to scale the obstacle using its front wheels, or they can

	also lift up each leg alternately and place it on the obstacle. ▪ Rolling/Jumping: Robots are designed to move on flat surfaces using their wheels and activate a jumping strategy with their legs to overcome obstacles. ▪ Legs and Wheels: This includes robots that use their legs and wheels separately, alternating between them for locomotion. They can also employ an additional arm to touch the top of an obstacle and pull themselves up. ▪ Legs and Tracks: These robots have both these types of locomotion systems but are separate from each other. On flat or sandy terrain, it moves using tracks, but when it encounters an obstacle it positions its legs on the ground, lifts its body, and walks over the obstacle. ▪ Legs with wheels/Rocker Bogie: Ex Spider-leg robot, with wheels attached to the Rocker Bogie mechanism, allowing them to move freely and adapt to the terrain's irregularities. The robot also has 2 legs allowing the robot to overcome small obstacles (could be used in a snake like robot). ▪ Legs, tracks, and wheels combines all three common types, ex Fig 17c, d and e. • Modular Robots: • Robots with Body Repositioning: • Robots with Additional Supports: • Principles that define strategies for overcoming obstacles: ○ **Adaption to Obstacle's Shape**: done with either active or passive mechanisms that allows traction generating elements to adapt to irregular terrain without losing contact with the ground. ○ **Use of Traction:** Traction is necessary for overcoming obstacles and this is done by mainly creating tractive forces friction. Traction needs to be large enough to provide thrust for robots to scale obstacles. ○ **Positioning Parts on the obstacle:** Involves placing parts of the robot on the obstacle even if those parts lose contact with the ground. Stability is ensured by the remaining parts of the robot still touching the ground. ○ **Redistribution of reaction forces:** Allows robot to modify the magnitude of reaction forces between

	traction elements of the robot and the ground, increasing reaction forces to enhance ground friction and decrease them to lift a part of the robot. This can be done using actuators. Article Summary: Robots and rovers operating on natural terrain will encounter complex obstacles that they need to overcome. This article provides an overview of 108 robots designed for this purpose and categorizes them based on similar features. They are divided into 3 categories based on their locomotion method – wheels, legged and tracks. Their suspension methods were also categorized into two types, active and passive suspensions. Hybrid mechanisms that combine two or more types of the three locomotion methods were also explored. At the end of the paper, 5 principles that would help determine the efficiency of the robot were also stated. These 5 principles were adaptation to the obstacles shape, use of traction, ability to position parts on top of the obstacle, distributing reaction forces and the ability to jump. Overall, these systems could be enhanced by incorporating A.I. to aid with complex decision making.
Research Question/Problem/ Need	To provide an overview of various different robot designs for overcoming obstacles and complex terrain.
Important Figures	 -

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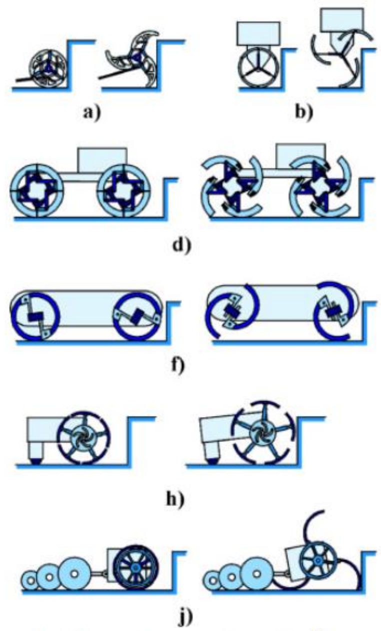

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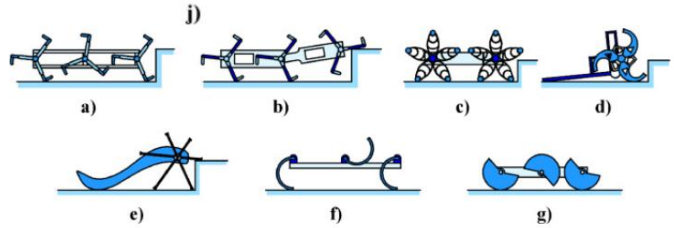

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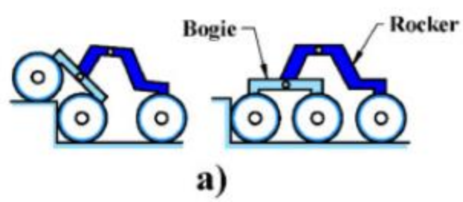

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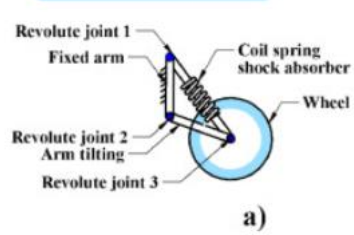

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<td>VOCAB: (w/definition)</td>
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Differential System: system essential for allowing the robot to move in various directions.
Concentric: Circles or arcs that share the same center.
Actuators: motors are basically a type of actuator; they convert an energy input into a mechanical output.

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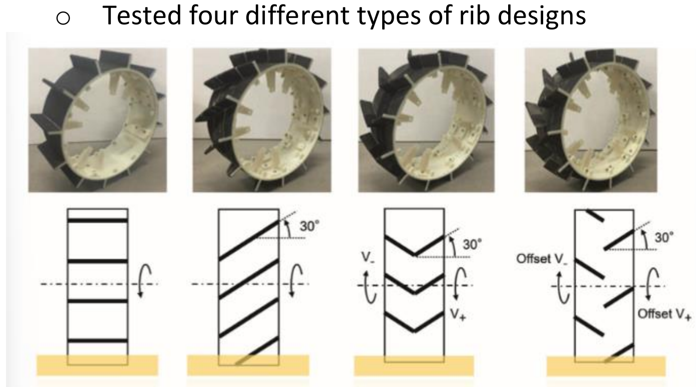
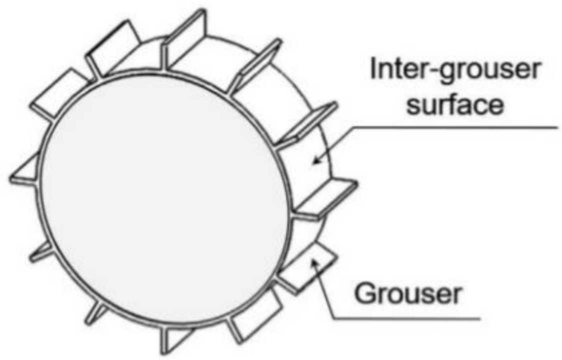
	• **Hexapods**: with six wheels • **Bipedal**: 2 Legs; **Quadrupedal**: 4 Legs; **Hexapods**: 6 legs; **Octopods:** 8 Legs
Cited references to follow up on	• Moosavian, S. A. A., Semsarilar H. & Kalantari, A., (2006). Design and Manufacturing of a Mobile Rescue Robot. *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, China, pp. 3982-3987. https://doi.org/10.1109/IROS.2006.281835 • Ma, Z. & Li, D., (2018). Suspension System Design of All-Terrain Fire-Fighting Robot. *2018 International Conference on Virtual Reality and Intelligent Systems (ICVRIS)*, Hunan, China, 2018, pp. 466-468. https://doi.org/10.1109/ICVRIS.2018.00120
Follow up Questions	• How exactly do Rocker Bogie and Linkage Mechanisms suspension system work? • Can the wheel with appendage robot be combined with soft robotics to allow the chassis to bend itself, enhancing its ability to overcome obstacles? • Do hybrid robots that both roll and walk face the danger of slipping because of the wheels at the end of their legs?

Article #7 Notes: Shape Effects of wheel grousers on traction performance on sandy terrain

Source Title	Science Direct
Source citation (APA Format)	Nagaoka, K., Sawada, K., & Yoshida, K. (2020). Shape effects of wheel grousers on traction performance on Sandy Terrain. *Journal of Terramechanics*, *90*, 23–30. https://doi.org/10.1016/j.jterra.2019.08.001
Original URL	Shape effects of wheel grousers on traction performance on sandy terrain - ScienceDirect
Source type	Science Journal
Keywords	Grouser Wheel; Effect of grouser shapes; Traction performance on sand; Exploration rover
#Tags	Grousers

Summary of key points + notes (include methodology)	• Grouser wheels enable rover to cut through large amounts of soil, improving traction performance
	• Examined wheel slip, sinkage, traction and side force on the wheel axle; and the driving torque and efficiency of each wheel
	• Test Wheel Design
	    ○ Composed of acrylonitrile butadiene styrene resin and 3D printing
	    ○ This produces a wheel sufficiently stiff for the testing purposes
	    ○ Rough material (sandpaper) was glued to the end of the wheel to minimize slippage between wheel and sand
	    ○ Tested four different types of rib designs
	•  (a) Parallel. (b) Slanted. (c) V-shaped. (d) Offset V-shaped.
	• Used **Toyoura sand** for their testbed

	• Slip conditions were simulated by applying a traction load (TL) that pulls the wheel backwards. Traction loads of 0, 0.44, 0.87, 1.3, 1.7, 2.1 and 2.5 kg were tested
	• Slip ratio (s) = [(r + lg) w-vx]/(r + lg)w; where r is wheel radius, lg is grouser height, w is angular velocity of wheel, and vx is wheel's velocity in horizontal direction
	    o In this paper rolling radius is just defined as r + lg
	
	
	(a) Schematic illustration.
	•
	• Results:
	    o Slip Ratio:
	        ▪ Slip ratio increases with an increase in traction load
	        ▪ Slip ratio is not impacted by the grouser shape during forward travel
	    o Sinkage:
	        ▪ Sinkage increases with an increase in slip ratio regardless of the grouser shape
	        ▪ Offset V grouser design shows the most sinkage at larger slip ratios, because of the high amount of escape paths for the sand in between the ridges.
	        ▪ Sinkage can also be measure by looking at the amount of sand that gathers behind the wheel at it tries to move forward
	    o Driving Torque:
	        ▪ Driving torque increases when slip ratio increases regardless of grouser shape
	        ▪ Grouser spacing (angle of the grouser rib) in parallel and V- grousers tends to fluctuate in low slip ratio condition, however this fluctuation is reduced in higher slip ratio.
	        ▪ Slanted and offset V shaped grousers have small fluctuations because of the continuousness of the ribs from the side
	    o Side Force:

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- Slanted grousers exert a larger side force, which is more pronounced at larger slip ratios (probably due to its asymmetry
- Side force in other grouser shapes does not change significantly

- Vehicle Performance:
  - Slanted 2 and V+ grouser shapes result in the least amount of side slip, while parallel grousers show the maximum
  - Slanted 2 also demonstrates improved slope travelability and uphill traction
  - Slanted grousers have a side force effect that is expected to enhance wheel performance on sandy terrain and slopes
- **Slanted grousers are the best for rovers**
- Testing: First, they tested each configuration on a single wheel testbed then on a four wheeled rover. The second testbed's incline is adjustable, allowing them to test rover various slopes

Article Summary:
Grousers are devices used to increase the traction of a vehicle on a sandy surface. Many different grouser shapes have been used in the past, for example the Curiosity Mars Rover has zig-zag shaped grousers while Perseverance has parallel grousers. While these different types have been tested in studied in sperate environments, they have never been directly compared to each other, which was the aim of this research paper. First, they conducted singe wheel tests for each grouser shape and studied properties such as slip ratio, sinkage, torque and side force on each wheel. Next, they conducted four-wheeled rover tests with each grouser shape to assess how well each grouser travels over sandy slopes. Studies showed that slanted grousers had the lowest side slip on slopes, thus making it the best grouser shape for planetary rovers.

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<td>Research Question/Problem/ Need</td>
<td>To investigate the effects of different grouser shapes on wheeled rover performance.</td>
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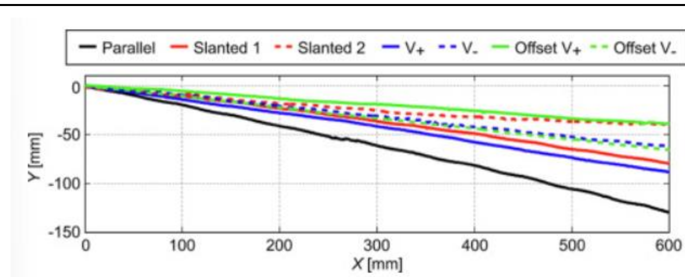

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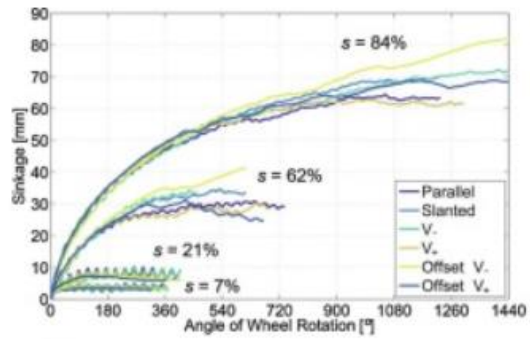
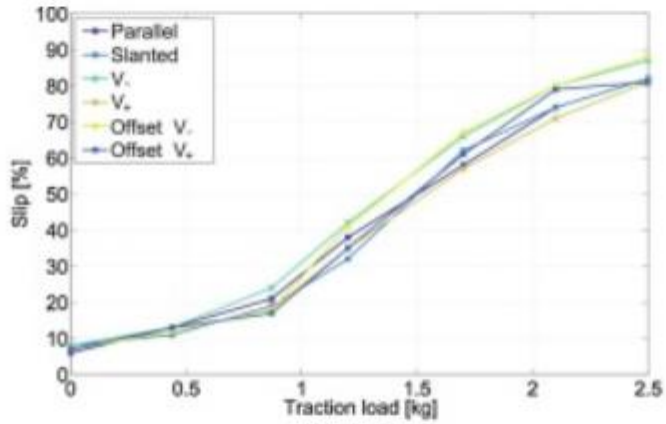
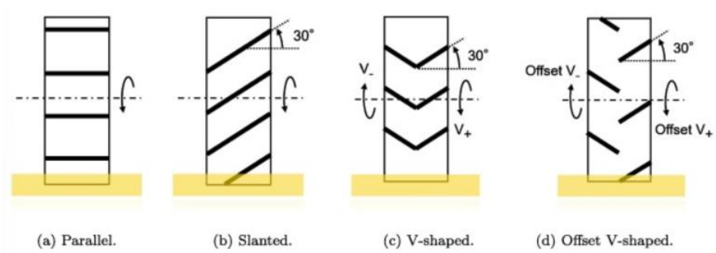
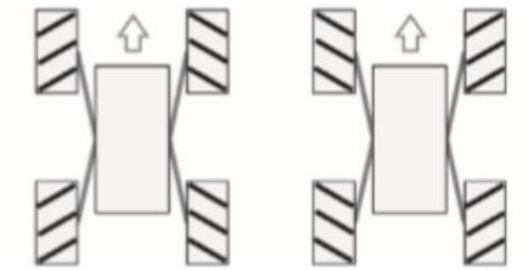
	 (b) Sinkage versus wheel rotation angle. -  (a) Slip ratio versus traction load. -  -
VOCAB: (w/definition)	• **Slip Ratio:** Measure of the difference between the actual speed of the vehicle's tire and speed it would be going without slipping (high slip ratio means the surface is too slippery) • **Wheel sinkage:** the distance from the bottom of the inter-grouser surface and the sand's surface • **Side Force:** The force acting in the lateral direction of the object (Ex when a car is turning around a corner)
Cited references to follow up on	• Sutoh, M. (2013). Design of wheels with grousers for planetary rovers. *Journal of Terramechanics*, 50, 345–353. https://doi.org/10.1016/j.jterra.2013.02.003 • Moreland, S., Skonieczny, K., Inotsume, H., & Wettergreen, D. (2012). Soil behavior of wheels with grousers for planetary

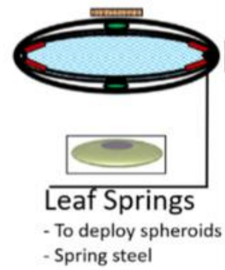
	rovers. *2012 IEEE Aerospace Conference*, 1-8. https://doi.org/10.1109/AERO.2012.6187040
Follow up Questions	• Can slanted grouser's side force be reduced by arranging them in an omni wheel chassis format? Yes, the current arrangement has a linear movement but will this configuration result in a reduced side force?  • How can the most efficient grouser design be paired with another method of locomotion (crawling?) to create the most efficient sand traversing robot? • Since grouser shapes that have a higher number of escape paths for the sand led to a greater amount of sinkage in the wheels, can the wheels be modified to have parts that cover their sides, preventing the escape of sand? Would that reduce traction capabilities?

Article #8 Notes: Single Wheel Test Rig for Ocean World Rovers

Source Title	Science Direct
Source citation (APA Format)	Girija, A. P., et al. (2023). A single wheel test rig for ocean world rovers. *Journal of Terramechanics*. https://doi.org/10.1016/j.jterra.2023.XXYYY
Original URL	A single wheel test rig for ocean world rovers - ScienceDirect
Source type	Scientific Journal
Keywords	Planetary Rover; Wheel; Test Rig; Mobility System; Ocean Worlds
#Tags	Locomotion Methods

Summary of key points + notes (include methodology)	• Small-diameter wheels, such as those used by Mars Rovers, are prone to slippage and sinkage in loose soil
	• Prior to getting stuck, Spirit experienced significant slippage
	• Single wheel test rigs are used to validate Terra mechanics models
	• Design and Fabrication of the Single Wheel Test Rig
	    ○ A test rig with a horizontally moving surface with the wheel held in place was considered, however this led to difficulties when the scientists wanted to test on a variety of surfaces (such as granular ice and boulder fields)
	    ○ **Decision:** use a static testbed with a horizontally moving wheel so that different surface conditions could be tested
	$s = \begin{cases} (r\omega - v_x)/r\omega & \text{if } \lvert r\omega \rvert > v_x, \text{ positiveslip} \\ (r\omega - v_x)/v_x & \text{if } \lvert r\omega \rvert < v_x, \text{ negativeslip} \end{cases}$
	    ○
	    ○ Most single wheel test rigs are designed to operate at speeds less than 10 cm/s
	    ○ Ideal test rig would be able to accommodate slip ratios from –1 to +1, however this would require an angular velocity that increases sharply as slip ratio approaches 1
	    ○ Vertical Load must also be controlled to simulate wheel-surface interactions with different surface gravities (requirement of vertical load on the wheel in the range of 20-400N)
	    ○ Slip angle and camber angle are defined as ±25 degrees, which they used to identify the minimum dimensions of their test rig
	• Mechanical System Design of Single Wheel Test Rig (Fig. 9 & 10 for test rig pics):
	    ○ Horizontal motion control of wheel is achieves using a

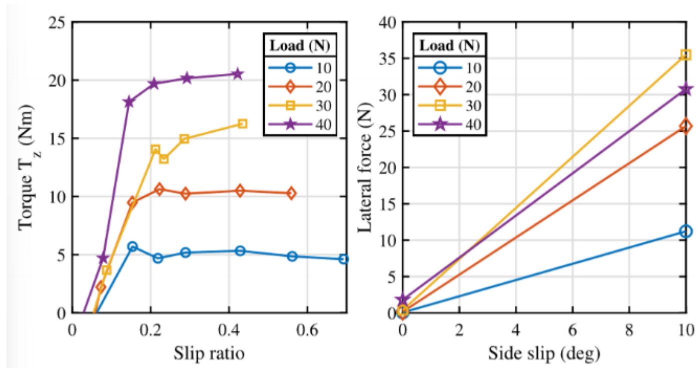
	carriage to support the wheel ○ The carriage is the primary moving structure, and supports the vertical load control and wheel drive mechanism that move along with the carriage ○ Carriage is controlled using a pulley, timing belt and motor ○ Top of the frame serve as guiderail for horizontal movement of carriage ○ Load control system is used to simulate wheel's motion in reduced gravity environment ○ Entire wheel assembly is supported on rollers and can move in vertical direction ○ Range of ±30 degrees for both slip and camber angle ○ Slip mechanism consists of a linear actuator that changes slip angle of the wheel-motor assemble arm ○ Six-axis force and torque sensor is mounted between the wheel and wheel mounting plate. Test rig also includes vertical load, slip angle, camber angle and horizontal and vertical draw wire sensors ○ Test bed is built to be modular and easily reconfigurable to simulate a wide range of surface conditions, because we don't yet have enough information about Europa's surface ○ Three motors, one each for horizontal carriage motion, wheel drive and camber mechanism ○ Two actuators for vertical load control and slip angle mechanism ○ Six-axis force sensor and torque sensor are the primary sensors which measure the three-axis forces and torques on the wheel • Prototype Wheel Fabrication: ○ All Mars Rover wheels to date have used wheels that are rigid and small primarily due to volume constraints ○ Ocean Worlds such as Europa would have more jagged and sharp terrain than Mars ○ Wheel should be capable of overcoming obstacles at least 0.5 meters in height ○ Exterior tire surface is unpressurized, with tension being provided by the spheroids ▪ The spheroids aren't pressurized either, they are given their structure with the help of leaf springs that force the spheroid's geometry



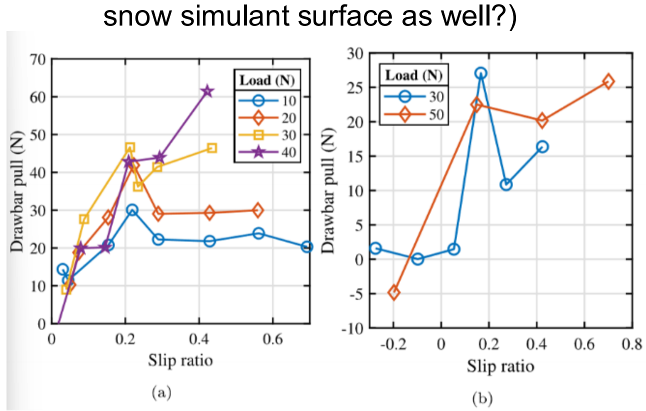
- Leaf Springs:
  - Annulus vessels are also located within the tire, along the circumferential path above and below the spheroids
    - These vessels are pressurized during the deployment process to expand the fabric and assemble wheel into its functional geometry
    - After deployment, only the inner annulus is required to be pressurized to ensure the spokes retain the wheel's shape (enabling tire to still function when punctured)
  - Reliability of tire can be increased by adding another inner annulus
  - According to Table 2 on pg 114, slip ratio of this wheel says very low, even with high vertical loads
  - Oblate spheroids are attached to a metallic rim
  - Check Fig. 23. For the data processing algorithm of the sensor data
  - The outer surface of the tire has 16 sleeves which have tubing stiffeners inserted into them, simulating tire threads (or even grousers)
- Test Results:
  - All tests were performed on two surfaces. Flat surface with sandpaper and ocean worlds surface simulant of glass beads
  - Traction force rapidly increases with increasing slip ratio, up to slip ratio of 0.2. After that traction increases only slightly.
  - Traction force also increases with increasing vertical loads
  - Torque increases sharply till slip ratio reaches 0.2, after which it flattens out
  - Torque increases with load

Article Summary:
The aim of this paper was to create a deployable wheel intended for effective mobility on Ocean Worlds such as Europa or Enceladus. This wheel would be subjected to extremely low temperatures and loose, slippery terrain. The test rig they designed in this paper is intended to test the mobility of a single wheel on various terrain when subjected to different vertical loads and slip angles. Next, they created a deployable wheel that could deform according to its surface. The wheel also had a large diameter as all planetary rover wheels to date were small and rigid. Test results show that the rover wheel is mostly

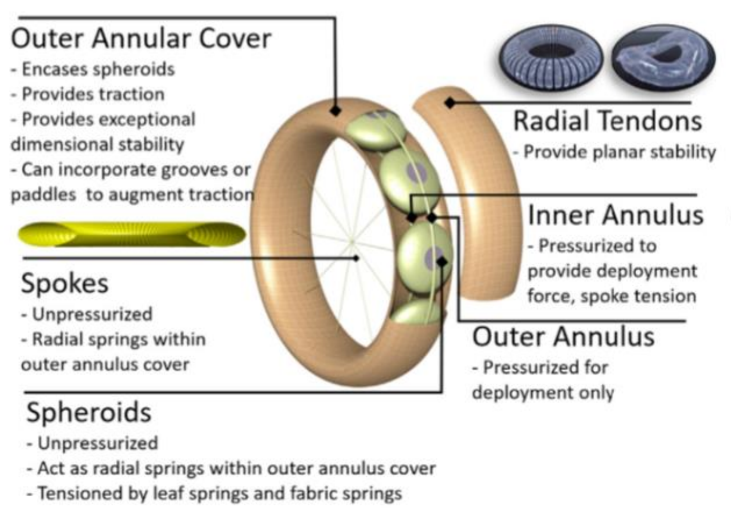
<table>
<tr><td></td><td>functional on loose terrain; however further testing and analysis is needed to verify its performance.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>How can we design a wheel mechanism that enables reliable mobility for planetary rovers on icy terrain such as Europa?</td></tr>
<tr><td>Important Figures</td><td>

- 

    - Shows results from flat surface testing (why not include snow simulant surface as well?)

- 

    - A is on flat rough surface, B is on snow simulant

- 

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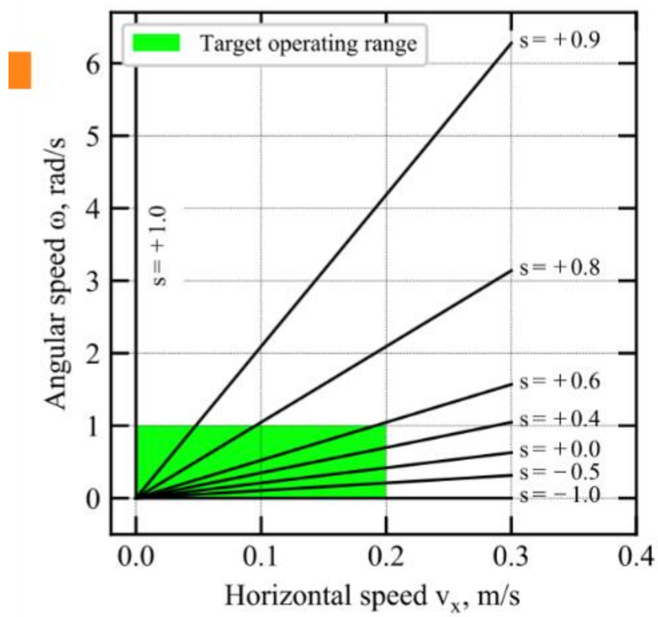
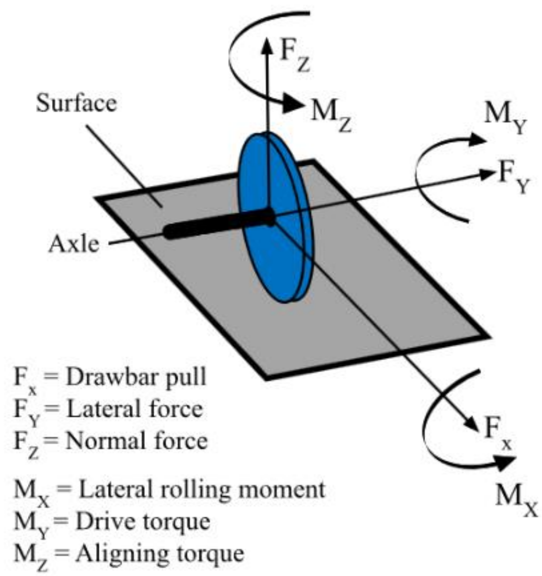
	 **Fig. 2.** Required wheel angular speed as a function of horizontal traverse speed at various slip ratios (for the prototype test wheel with diameter = 0.956 m). -  **Fig. 7.** Wheel forces and moments. -
VOCAB: (w/definition)	• **Camber Angle:** The angle between the vertical axis of a wheel and the vertical axis of the vehicle • **Positive Slip:** when the wheel's angular velocity is greater than its zero-slip velocity, generating a force that speeds up the vehicle • **Negative Slip:** when the wheel's angular velocity is less than its zero-slip velocity, generating a force that slows down the vehicle • **Slip Angle:** the angle between the direction of a vehicle's travel and a

	wheel's direction of travel (from top view) • **Annulus:** ring shaped • **Drawbar Pull Force:** (a.k.a. Traction Force) The amount of horizontal force available to a vehicle when pulling a load
Cited references to follow up on	• Lorenz, R.D., Zimbelman, J.R. (2014). Moving on Sand. In: Dune Worlds. Springer Praxis Books(). *Springer,* Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-89725-5_22 • Muirhead, B. K. (2020). Mars sample return campaign concept status. Acta Astronautica, 170, 513–524. https://doi.org/10.1016/j.actaastronautica.2020.10.017
Follow up Questions	• How does the slip angle affect the slip ratio of the wheels? • Can inflatable wheels be used instead of small wheels, to both fit the volume constraint while still being able to increase wheel radius, potentially preventing sinkage? • Would the loose soil deform under the deformable as well?

Article #9 Notes: Origami Wheel Design for Sandy Terrain

Source Title	Cambridge University Press
Source citation (APA Format)	Hu, J., Shu, S., & Han, W. (2024). A novel mobile robot with origami wheels designed for navigating sandy terrains. *Robotica*, *42*(11), 3731–3747. https://doi.org/10.1017/S0263574724001619
Original URL	A novel mobile robot with origami wheels designed for navigating sandy terrains | Robotica | Cambridge Core
Source type	Academic Platform
Keywords	Origami mobile robot; sandy terrains; Kresling origami; slipping ratio; origami wheel
#Tags	Locomotion Methods

Summary of key points + notes (include methodology)	• Sand can exhibit both liquid-like and solid-like behavior, depending on its interaction with the robotic system
	• Traditional robots become trapped in loose sand due to their weight and lack of the propulsive force that moves them out of the trap.
	• Origami Sand Robot Design:
	  ○ Used polylactic acid to minimize the weight of the robot
	  ○ Origami wheel made of 0.2mm pure titanium sheet
	  ○ The concave creases in the origami wheels acts as grousers as well
	  ○ As shown in Fig.3. The motor generates torque (Tt) which acts in the direction the rover is going in, and under the influence of torque the wheel exerts a rim (F0) on the sand. A reaction force (Ft) is exerted by the sand, causing the vehicle to move forward
	  ○ When there isn't any slippage between the sand and origami wheel, reaction force from the sand acts along the circumference of the wheel
	  ○ By manipulating the folding and unfolding of the wheel, the wheel's spine pattern, its depth and contact area with the sand will vary, influencing the propulsive force and friction between the wheel and terrain
	  ○ The Kesling origami structure in enclosed within 2 thin round plates that are 2mm thick and made of

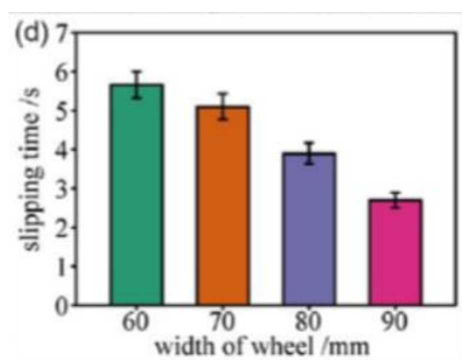
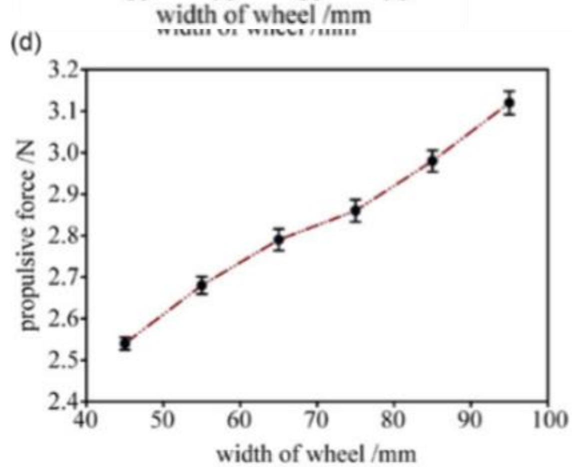
	acrylic o To control the wheel's width, 2 telescopic rods are used with an inbuilt linear motor, to expand and contract the wheel ▪ Rod 1 controls the width of the left wheels, while rod 2 controls the width of the right wheels ▪ Range of width for robot's wheels is from 45 to 95mm ▪ Ratio of maximum and minimum width is 19/9 (approx. 2:1) • Performance of Sand Robot: o Tested robot in a controlled flat sand environment (2.6m length, 1.2m width and 50mm thick) o Locomotion capabilities: ▪ First investigated how the rotational speed of the wheel affected the robot's mobility, by setting the origami wheel's speeds at intervals from 20 to 140 rpm ▪ When set at its maximum value of 140rpm, the robot had a velocity of 56cm/s, showing that the origami wheels had the potential for swift movement on sandy terrain ▪ Tested the effect of different wheel widths on the velocity of the robot by testing the origami wheels with widths of 45, 70 and 90mm with rotational speed of 40rpm ▪ Velocity of robot shows a slight increase with the increase in wheel width (from 15 to 17 cm/s) ▪ Used attitude transducers to measure velocity and acceleration of wheels ▪ Wheels need some time to accelerate from rest before moving, and so to study the effect of the wheel's width on this starting acceleration they studied the robot's acceleration with wheel widths from 45 to 90mm. Robot exhibited a higher acceleration with an increase in width, as shown in the graph in Fig. 5(d). ▪ Increasing wheel speeds also led to a higher acceleration ▪ Robot also shows the ability to traverse wet sandy terrain ▪ Robot's velocity decreases as the depth of the wheel's sinkage increases, as shown in Fig. 6(c)

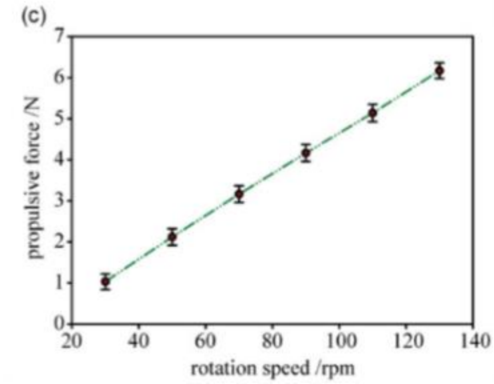
- Slip resistance of robot is enhanced by increasing the number of concave origami surfaces resembling thorns on the wheels
- Slip rate is also higher on wet sand than compared to dry sand
- When the "V" shaped spine/grouser of the wheel comes into contact with the sand's surface, a pressure is generated between the wheel surface and sand, resulting in friction/grip force which prevents the sliding of the wheels on the sand. The horizontal component of this force propels the robot forward.
- **Driving force relies on both the positive pressure between folding surface of wheel and sand, and the area between the spine's faces for adhesion**
- Widening origami wheel increases the V-shaped concave angle formed by the spine (theta), enlarging contact area with the sand, thus resisting sliding while also providing a larger propulsive force
- To prevent slippage, it is important to use material with a high coefficient of friction
- Increasing wheel width also decreases sideway sliding or skidding, as this increase that friction between wheel and sand
- Origami wheels exhibit a higher sliding rate in wet sand
- Larger wheel diameters reduce robot slippage on sandy surfaces

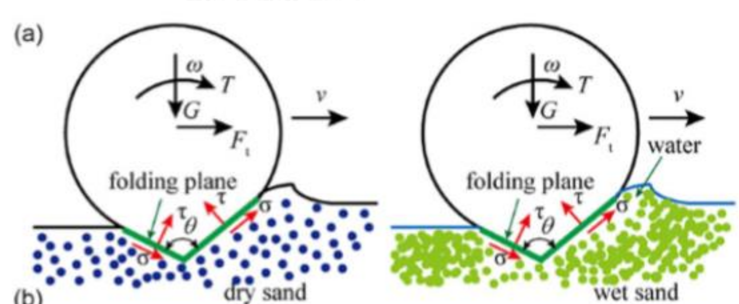
- Propulsive Force Analysis:
  - Use a push-pull dynamometer to measure propulsive force
  - As rotational speed increases, so does the propulsive force, as shown in Fig. 7(c)
  - Propulsive force also increases with an increase in wheel width, as shown in Fig. 7(d)
    - When the width starts increased to more than 75mm, the depth of the concave region (spine/grouser like) of the wheel is reduced, thus decreasing surface contact area and causing a slight decrease in the propulsive force
- Steering Performance of Sand Robot:
  - Used a gyroscope to gather data on steering angle and angular velocity to study the

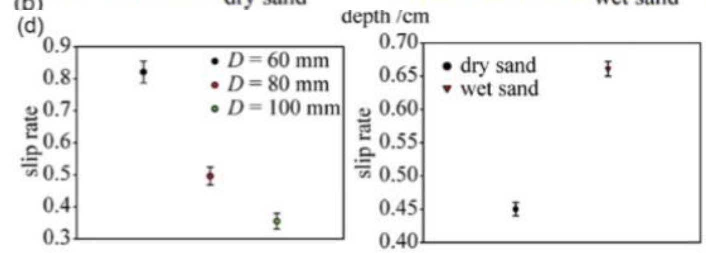
	origami wheel's steering characteristics ▪ Steering is determined by the speed difference between the inner and outer wheels, so they studied how this speed difference affects steering velocity and steering radius in the origami wheel rover ▪ Turning radius is calculated by 2/[d x (vo + vo/vi - vi)], where d is the distance between the two wheels, vo is speed of outer wheel, and vi is speed of the inner wheel ▪ Higher differences in left and right wheel rotational velocities had a smaller turning radius, while lower differences in rotational velocities had a larger turning radius Fig. 8(b). ▪ Higher angular velocity had a higher steering speed Fig. 8(c) ▪ Wheel width didn't affect the steering radius much Fig. 8 ▪ Steering speed increases with an increase in wheel width (Fig. 8.) since wider wheels provide a greater propulsive force. ▪ Conducted experimental analysis to discover these findings. o Capability to traverse an inclined plane: ▪ Measuring the robot's slippage is crucial to measuring how well the robot can climb sloped terrain ▪ In this paper, the slip ratio is defined as 1 - (vr/va) where vr is the velocity of the robot and va is the circular velocity of the origami wheel. Va is equal to 2πrω, where r is the radius of the wheel, and ω is the rotational speed of the wheel. • Slip rate ranges from 0 to 1 for the origami wheel, where 0 indicates no likelihood of slippage, while 1 indicates significant slippage. ▪ Climbing performance was assessed by creating a sand pile with angles ranging from 5 to 20 degrees and testing the robot's capabilities on it ▪ As the angle of the slope increases, so does the likelihood of the robot slipping ▪ Experimental testing showed that the robot had a lower slip rate at higher angle slopes when its wheels had a smaller width ▪ When the wheels had a larger width, they

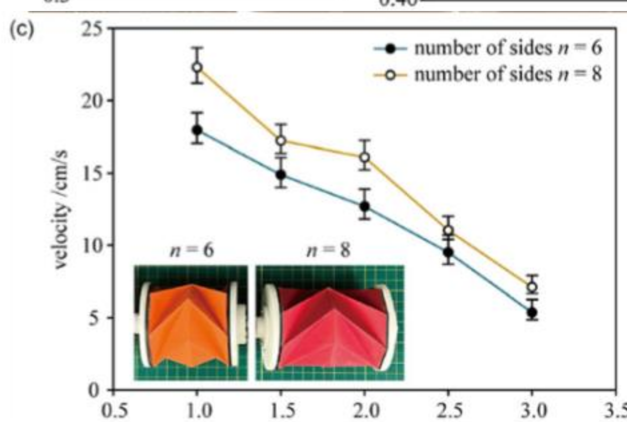
	were able to more effectively overcome the slope, without sinking Fig. 9(b) ▪ Slip time of robot increases with lower wheel widths ▪ Traditional cylindrical wheels have a slip rate of 0.82 while the origami robot with 6 – 8 spines had a slip rate from 0.4 to 0.5. ▪ More spines = lower slip rate o Capacity of crossing narrow passageways: ▪ The robot can change its width to fit through narrow passageways, as shown in the picture of the experimental test Fig. 10. o Loading Capacity of the Sandy Robot: ▪ Increase in weight causes increase in sinkage ▪ Origami wheels have a high load bearing ratio because of how lightweight they are. ▪ Increasing width of wheels also increases robot's carry capacity because of the increase in contact area with the sand, and the robot's propulsion force. ▪ Increasing robot's rotational speed also increases it's carrying capacity, which improved load bearing ratio from 2.1 to 3.2 (meaning robot can carry 3 times is own weight) ▪ Achieving equivalent wheel widths requires a higher driving force to widen the wheel when robot is subjected to higher loads o Summary: ▪ Robot can adapt to a variety of situations that are usually encountered when navigating sandy terrain, such as narrow channels, sand slopes, and curved paths ▪ Increasing wheel width results in a larger velocity when moving across a flat and sandy surface ▪ Reducing width increase ability of robot to fit through narrow channels ▪ Increasing wheel width improves ability of robot to climb sandy slopes while also decreasing its slip ratio ▪ Adjusting different rotational speeds allows the robot to turn on the sand • Conclusion: o Adaptable wheels enable the robot to complete tasks like traversing slopes and narrow channels, which is difficult for traditional rigid wheeled robots

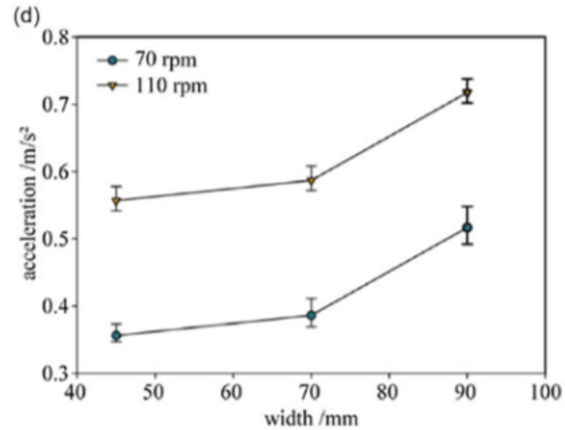
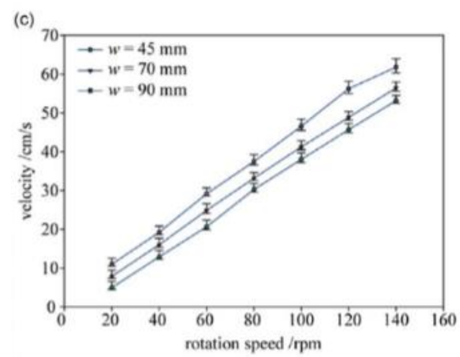
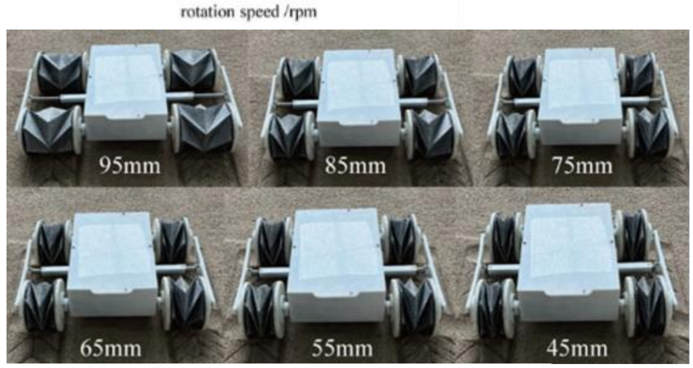
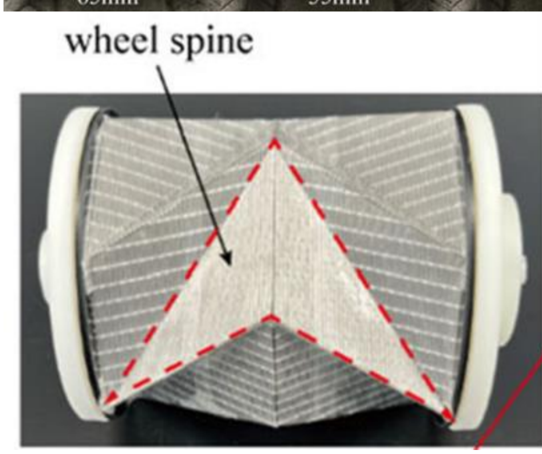
	○ Performed experimental tests to evaluate how varying the wheel width affects properties such as velocity, propulsive force, climbing capability, and carrying capacity Article Summary: Robots that can effectively traverse sandy terrain are crucial to understanding deserted regions on earth, or even for the exploration of other planets that have similar terrain, such as Mars. Sandy areas are often complex, filled with features such as sand dunes and sand pits. To address this issue, scientists Hu et.al designed a robot with Kresling origami wheels that improve the velocity, acceleration and carrying capacity of the robot, while also decreasing slip rate and sinkage. The wheels of the robot can adapt to various obstacles found in sandy areas by increasing the width of their wheels. They discovered these properties of the origami wheels through a series of experimental testing on a sand test bed. While the design is largely successful, there is still more research that needs to be done to find why exactly this change in wheel shape improves the mobility of the robot.
Research Question/Problem/ Need	How does the wheel width affect properties such as velocity, propulsive force, carry capacity and climbing capability of robots on sandy terrain?
Important Figures	-  - 

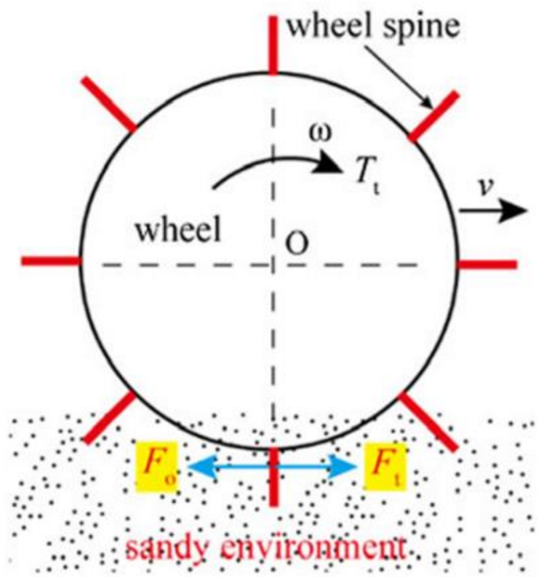

(c)
propulsive force /N
rotation speed /rpm
0
1
2
3
4
5
6
7
20
40
60
80
100
120
140


(a)
ω
T
G
F_t
v
folding plane
τ
θ
σ
dry sand
water
wet sand


(b)
(d)
depth /cm
slip rate
D = 60 mm
D = 80 mm
D = 100 mm
0.3
0.4
0.5
0.6
0.7
0.8
0.9
dry sand
wet sand
0.40
0.45
0.50
0.55
0.60
0.65
0.70


(c)
velocity /cm/s
number of sides n = 6
number of sides n = 8
n = 6
n = 8
0
5
10
15
20
25
0.5
1.0
1.5
2.0
2.5
3.0
3.5

- 
(d)
70 rpm
110 rpm
acceleration /m/s²
width /mm
- 
(c)
w = 45 mm
w = 70 mm
w = 90 mm
velocity /cm/s
rotation speed /rpm
- 
95mm
85mm
75mm
65mm
55mm
45mm
- 
wheel spine

	 -
VOCAB: (w/definition)	• **Transducer:** a device that converts one form of energy to another • **Interfacial:** included between two faces of a material • **Coefficient of Friction:** the ratio of frictional forces opposing motion between 2 surfaces and the normal force pressing them together • **Loading Capacity:** the ability of a robot to carry an amount of weight while ensuring it movement isn't interrupted • **Load Bearing Ratio:** ratio between an object's carrying capacity and its own weight
Cited references to follow up on	• Wang, J., Yao, Y., & Kong, X. (2018). A reconfigurable tri-prism mobile robot with eight modes. *Robotica*, 36(10), 1454–1476. https://doi.org/10.1017/S0263574718000498 • Ding, L. (2011). Experimental study and analysis on driving wheels' interaction with soil. Journal of Terramechanics. https://doi.org/10.1016/j.jterra.2010.06.001
Follow up Questions	• Would an origami wheel that goes all across the width of the robot underneath it improves velocity and traction, because the width of the wheel would be as large as the robot? • What modification would need to be made in order to better equip this robot for specifically loose sand? • How can other grouser shapes be replicated using origami, rather than only the V-shaped grouser?

Article #10 Notes: Locomotion Performance of Paddle Wheel Robot on Sandy Terrain

Source Title	Institute of Electrical and Electronics Engineers (IEEE)
Source citation (APA Format)	Shen, Y., Ma, S., Zhang, G., & Inoue, S. (2020). Locomotion performance of a configurable paddle-wheel robot over dry sandy terrain. *In 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 6453–6458. https://doi.org/10.1109/IROS45743.2020.9340828
Original URL	Locomotion Performance of a Configurable Paddle-Wheel Robot over Dry Sandy Terrain | IEEE Conference Publication | IEEE Xplore
Source type	Scientific Journal
Keywords	Vibrations; Shafts; Resistance; Wheels; Soil; Mobile robots; Robots
#Tags	Locomotion Methods

Summary of key points + notes (include methodology)	• Complex terrain can generally be classified into two categories: Rigid (which would include hard obstacles, such as rocks and gravel) and Soft (includes material that will deform under robot's wheels, such as sand and snow)
	  ○ **Soft material can also behave like a fluid, depending on how robot/rover interacts with it**
	  ○ Soft medium can be separating in dry and wet materials, and dryness/wetness of the terrain affects the existence of cohesion
	  ○ Most existing work focuses on dry soft terrain
	• Mechanism of Configurable Paddle Wheel:
	  ○ Mainly consists of 4 paddles, each connected to the paddle shaft in such a way that the paddles can rotate freely around the shaft
	  ○ Each paddle goes through evenly spaced hinges around the outer shell of the wheel, allowing their angle to be adjustable
	  ○ Paddle position is controlled with a planetary gear system
	  ○ 3 motors are used in one wheel: 1 for wheel rotation, sun gear rotation, and planet carrier rotation
	  ○ The position and angle of the paddle changes with the eccentric distance of paddle shaft
	    ▪ Length of protruding part of the paddle closest to the surface decreases when the eccentric distance is increased
	• Paddle Terradynamics:
	  ○ The potential fluid-like characteristics of soft granular media makes wheel-sand interactions more complex than compared to rigid granular media
	  ○ Analyzed the paddle terradynamics theoretically and experimentally

	(because of its complexity) o Interaction between wheel paddle and sand only exists on the length of the paddle inserted into the sand o Horizontal and vertical interface stress along the inserted part is assumed to be proportional to the sinkage of the wheel uses a model from reference [10] to make this assumption o Experimental Test: ▪ Wheel joint rotational speed was set to be pi/18 rad/s ▪ Looked at the experimental forces with 4 eccentric distances ▪ Experimental data verifies the theoretical model ▪ Deeper intrusion of the paddle into the surface (caused by smaller eccentric distance) generates larger interaction forces in both the vertical and horizontal directions of the wheel ▪ Larger forces in vertical direction could result in the vibration of the robot system, potentially causing damage ▪ The magnitude of the positive and negative forces in the Z-direction isn't equal, **suggesting that it is harder to push the paddle into the soil than to remove it from the soil**. • Locomotion Performance: o Paddle wheel generates larger propulsive forces with smaller eccentric distances o Also conducted single wheel, then whole robot test (similar to grouser shapes article) o Single Paddle Wheel Test (Indoors) ▪ Uses a testbed with two degrees of freedom (not counting Z-axis) ▪ Sandbox dimension: 1150mm long, 600mm wide, and 200mm deep ▪ Angular velocity was also changed, along with the eccentric distance, during these tests ▪ Horizontal velocity, variation in wheel height and rotational speed of motor were recorded in these tests ▪ Specific resistance is used to measure the efficiency of the form of locomotion. SR is defined as P (power consumed by the motor)/ [W (gravity of the system) x v (avg forward speed of wheel)] • Smaller SR means higher efficiency ▪ Sand was leveled before each test to minimize error ▪ Results: 1) Locomotion speed goes up with a larger angular velocity. 2) Increase in speed = increase in sinkage. 3) Slippage happened between wheel and sand at higher rotational velocities. 4) The wheel only configuration was the most inefficient. 5) When angular velocity is < 2.25rad/s, SR =10, which is the most efficient. 6) Small eccentric distances cause higher speeds and more efficiency; however, it causes vibrations to the system as well o Paddle Wheeled Robot (Outdoors)

<table>
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Experiments conducted with different configurations of the paddles and wheel joint velocities
Motor currents are the largest in the paddle-support configuration, while the least in the traditional wheel-support system
Hybrid-support system is the most efficient
Locomotion speed increases with the actuating velocity at almost a constant rate
Inefficiency at low speeds is likely due to the resistance from the terrain at first

Paddle-support configuration (rs = 0mm or 10mm) is most efficient on laboratory sand, while Hybrid-support configuration works best on the outdoor test bed with Sand #2

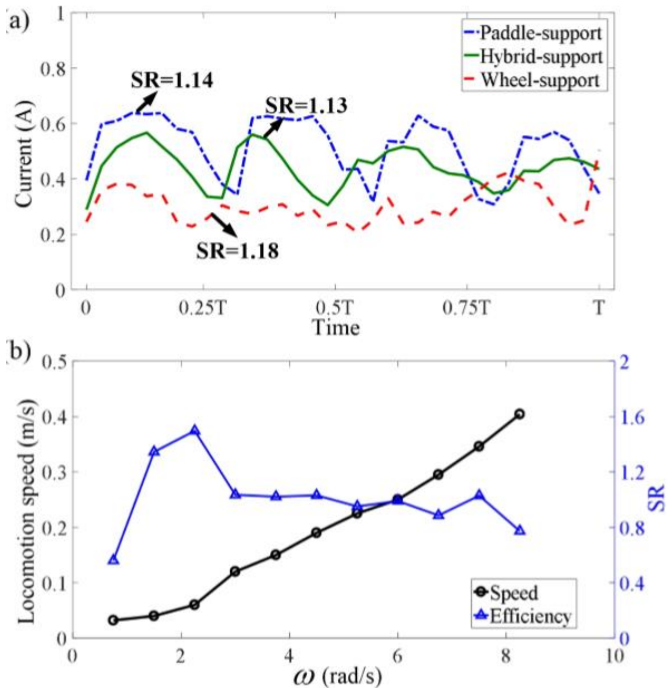
Could have happened because of the ability to change the weight of the rover in the indoor test
Another reason could be the type of sand being used (more difficult to insert paddle into sand 2 due to its larger particle size
Both these aspects affect the sinkage of the system, which also impacts the traction and resistance force

Optimal configuration depends on the characteristics of the soil and the total inertia of the system

Conclusion:
Wheel-only support configuration makes it easier for the robot to slip at higher speeds, but the protruding paddles can help prevent this

</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>Problem: Robots have difficulty navigating rough and sandy terrain efficiently.</td></tr>
</table>

Important Figures



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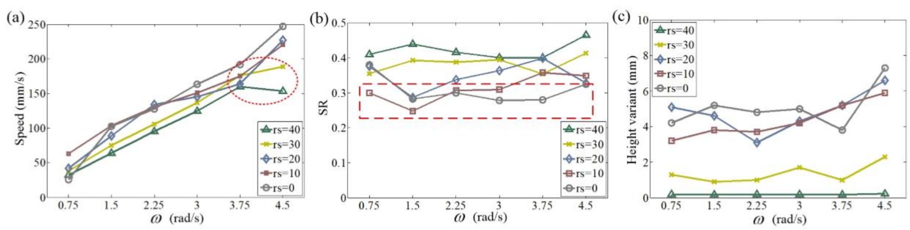
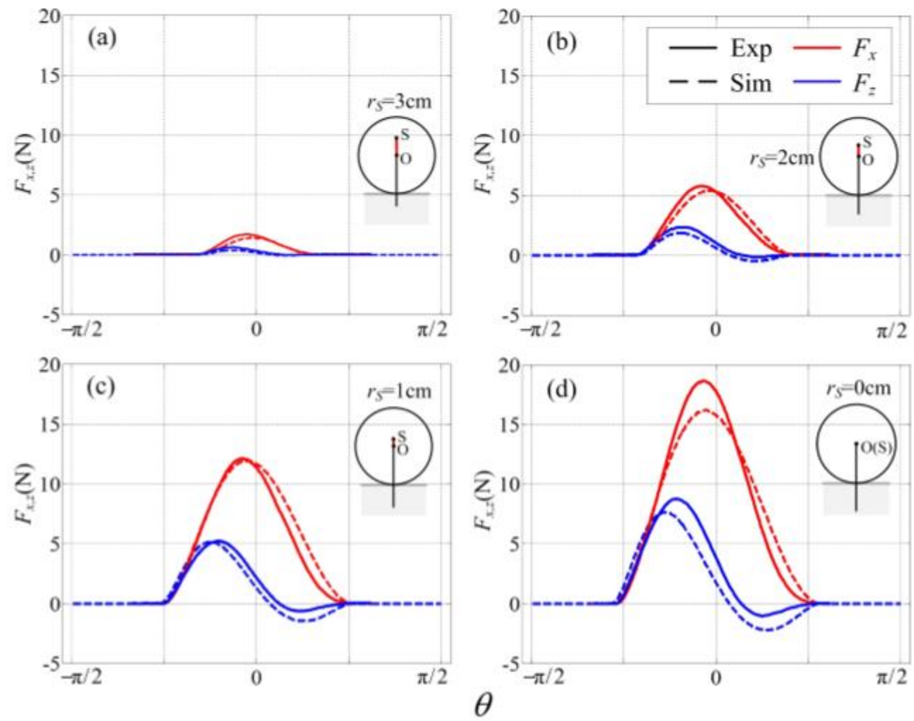


- Fig. 9. Experimental results of one paddle-wheel tests: (a) forward locomotion speed of the paddle wheel; (b) specific resistance; (c) height variant.

Compares different values to the rotational speed of the wheel, with different eccentric distances



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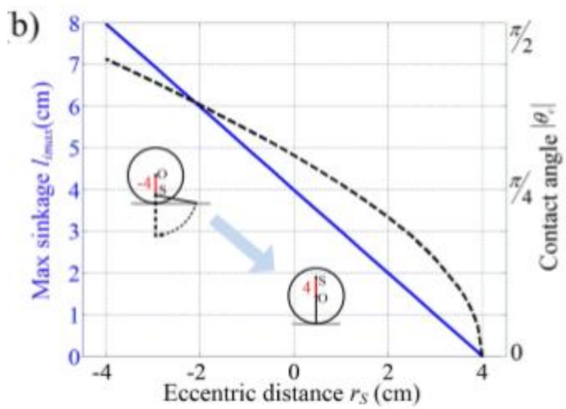

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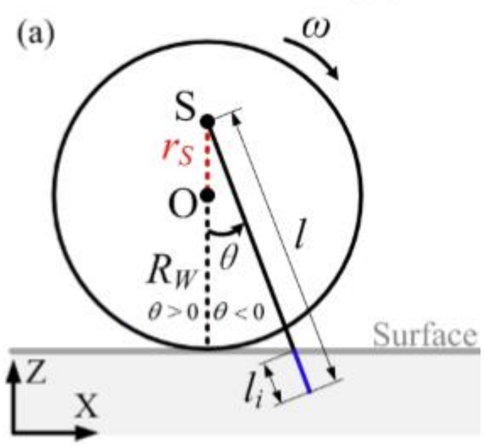

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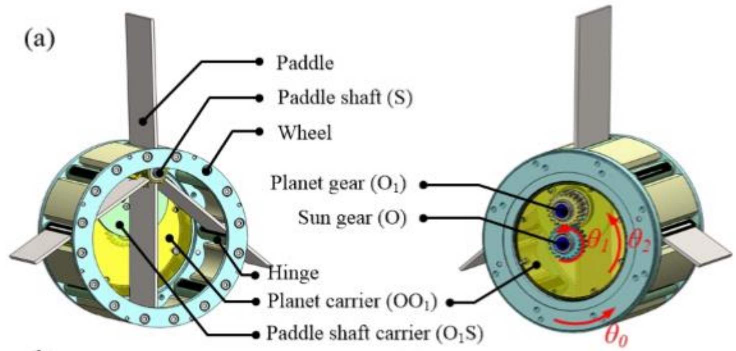
Force model of wheel when right when it's contacting the surface, when

	its sinkage is zero 
VOCAB: (w/definition)	• **Substrate:** the base material on which processing is conducted • **Interface Stress:** a surface thermodynamics quantity associated with the reversible work of elastically straining an internal solid interface • **Fourier Transform:** mathematical tools used to convert a function time into function of frequency
Cited references to follow up on	• Li, C., Umbanhowar, P. B., Komsuoglu, H., & Goldman, D. I. (2010). The effect of limb kinematics on the speed of a legged robot on granular media. *Experimental Mechanics*, 50(9), 1383–1393. https://doi.org/10.1007/s11340-010-9347-1 • Mazouchova, N., Umbanhowar, P. B., & Goldman, D. I. (2013). Flipper-driven terrestrial locomotion of a sea turtle-inspired robot. Bioinspiration & *Biomimetics*, 8(2), 026007. https://doi.org/10.1088/1748-3182/8/2/026007 • Marvi, H., Gong, C., Gravish, N., Astley, H., Travers, M., Hatton, R. L., Mendelson, J. R., Choset, H., Hu, D. L., & Goldman, D. I. (2014). Sidewinding with minimal slip: Snake and robot ascent of sandy slopes. *Science*, 346(6206), 224–229. https://doi.org/10.1126/science.1255718
Follow up Questions	• Why do most existing studies on soft terrain focus on dry granular media? What factors need to be changed when studying wet granular media instead? • How can vibrations in the system from higher speeds be reduced? • What types of sensors would be needed to automatically configure the wheels according to the surface?

Article #11 Notes: Geological Characteristics and Targets of High Scientific Interest on Mars

Source Title	Geophysical Research Letters
Source citation (APA Format)	Zhao, J., Xiao, Z., Huang, J., Head, J. W., Wang, J., Shi, Y., Wu, B., & Wang, L. (2021). Geological characteristics and targets of high scientific interest in the Zhurong landing region on Mars (Research Report). *Geophysical Research Letters, 48*(20), Article e2021GL094903. https://doi.org/10.1029/2021GL094903
Original URL	Geological Characteristics and Targets of High Scientific Interest in the Zhurong Landing Region on Mars
Source type	Peer-reviewed Scientific Journal Article
Keywords	Mars exploration; Tianwen-1 mission; Landing site selection; Geological characteristics; Scientific targets
#Tags	“Mars”, “Terrain”

Summary of key points + notes (include methodology)	• The Tianwen-1 mission to Mars consisted of a rover named Zhurong. The goal of the rover was to study the surface composition of Mars, the planet’s water-ice distribution, magnetic field and the environment of the surface
	• Rover landed near the southern part of the Utopia Planitia, with the Elysium volcanic province to its East and Isidis basin to the southwest
	• Methods of Data Collection:
	  ○ Used the Mars Orbiter Laser Altimeter (MOLA) and Mission Experiment Gridder Data Record (MEGDR) to visualize the physical features of the Zhurong landing region
	  ○ The Thermal Emission Imaging System (THEMIS) provided us with geomorphological information about the surrounding region.
	  ○ Pictures from the Context Camera (CTK) the High-Resolution Imaging Science Experiment
	• Results:
	  ○ The south of the study region has more mountains, valleys, and elevated terrain, probably due to the Utopia basin’s slope
	  ○ Used THERMIS to evaluate the thermal inertia of the region. Soil with larger effective particle size is indicated by warmer colors, while smaller particle sizes is shown with cooler colors
	  ○ Ejecta of impact craters have a higher thermal inertia

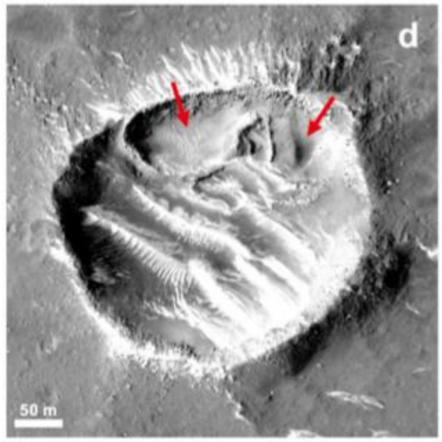
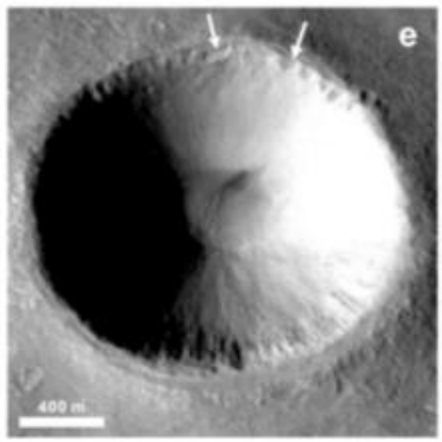
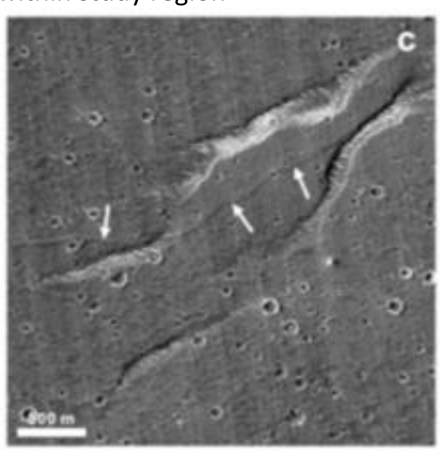
- Areas with low thermal inertia were usually cones and troughs (these areas also contain aeolian bedforms)
- Thermal inertia of the region indicates an effective particle size of larger than 1mm
- Max temperature is 296 K and minimum temperature is 186 K

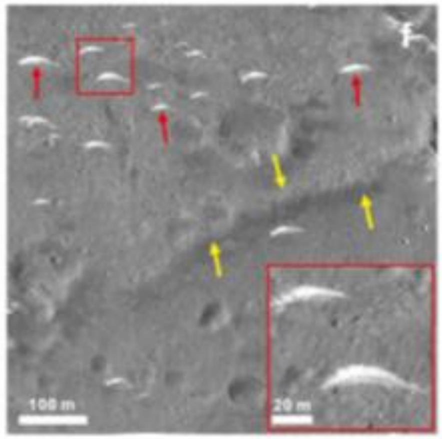
- Geological Features of the Study Region:
  - Cones:
    - Small, cone-shaped geological features that protrude outward from the Martian surface; usually found near volcanic plains
    - More than 10 cones were found in the study region, most of them surrounded by circular summit craters (bowl-shaped depressions usually located at the tops of elevated features)
    - Aeolian bedforms surrounded one of the cones in a radial pattern
  - Polygonal Troughs:
    - Long, narrow, steep-walled depressions typically formed due to crustal stretching and erosion
    - Dozens of throughs were found in the study region
    - Length varied from 1.1 to 8km; width was around 0.1 to 1 km
    - Trough depth was around 6 – 60m, with the average being 24m
    - These troughs are part of the polygonal through system in the Utopian Planitia
    - Aeolian bedforms occur parallel to the trough
  - Ridges:
    - Ridges are long, narrow, raised landforms, that often form because of tectonic forces, erosion, lava flows, or ancient water activity
    - Mapped tens of ridges within the study region
    - Lengths vary between 0.4 and 5.6 km
    - Often have rounded crests, and exhibit characteristics different from the wrinkle ridges found on volcanic plains
    - These ridges can be divided into 2 types: Type 1 is found a lot in the study region, and are troughs that are relatively short and straight; Type 2's are rarer and usually larger in length
  - Impact Craters:

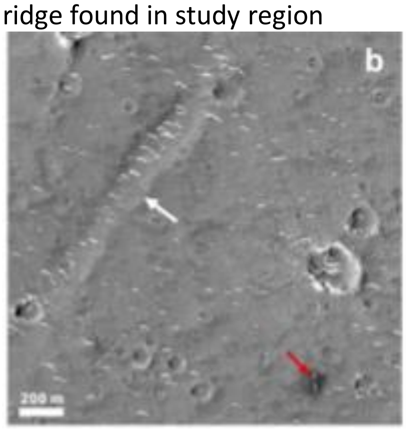
	- Depressions formed when an object (such as a meteoroid, asteroid or comet) collides with the planet's surface - Found 436 craters, out of which 12 had a diameter larger than 500m, while the others had a diameter in between 200 - 500m - Many rocky ejecta craters (RECs) have also been found throughout the region (they were identified by their higher temperature at night with THEMIS - Rims of RECs usually appear sharp, and they need to have a minimum diameter of 10 m - 40 craters had raised rim pits (shallow irregular depressions surrounded by elevated rims, making them look like tiny craters, but they were not formed by an impact) on their equator-facing walls - The largest impact crater, within the study region, has a concentric ejecta blanket (layered deposits of material that surround Martian impact craters) and rim pits near the uppermost part of the equator facing wall ○ Aeolian Features: - Occur within craters, polygonal troughs, cones etc. (shown by the lighter toned areas) - Mostly formed due to granule ripples and complex dunes - Bedforms are 10s to 100s of meters in length - Most occur in the direction of Northwest to southeast and east to west, however it depends on the topography in low regions and around cones ○ Absolute Model Age - Study region has a mostly uniform surface texture - Measured the impact crater size-frequency distribution measurements to better estimate the age of the study region - Results of the estimation indicate that approx. age of the region is 757 +- 66 Ma (Megaannum, or million years ago) • Targets for the Zhurong Rover ○ Cone A: - Cone A has 3 possible causes of origin: 1) Cinder cone (meaning it formed from the explosive eruption of lava fragments, specifically cinders); 2) volcanic rootless

	construct; or 3) a mud volcano ▪ Had to come to a conclusion using only satellite images, so the Zhurong rover would be the first high-resolution analysis of these geological features ▪ The RoPeR on the rover could be used to study the mineralogy and composition of the cone o Pitted-Wall Craters: ▪ Closest pitted wall crater is 0.5m from the rover's landing site ▪ Rim of pits likely formed relatively recently ▪ Likely formed by the release of volatiles or sublimation of ice near the surface, although how exactly this happened is not clear ▪ Exploration by the rover would provide a detailed analysis of the materials inside and outside the pits, to help us understand if the crater was formed due to an explosion or a collapse ▪ RoPeR could also provide insights on the water-ice and CO2 distribution near the surface of these craters o Aeolian Bedforms: ▪ Aeolian landforms can tell us the direction of the Martian winds ▪ While images show us the direction of the winds, we cannot tell how recently they occurred ▪ In-situ observations by the rover can help us study the relationship between aeolian bedforms, providing us with information to answer some of these questions ▪ Light-toned bedforms may contain sulphate minerals, and so the rover's in-situ exploration would tell us more about the origin of these features o Polygonal Troughs: ▪ Polygonal troughs have been thought to relate to activity of volatile substances ▪ 3 theories of their formation have been proposed: tectonic uplift model; drape folding model; and volumetric compaction model ▪ The volumetric compaction model is the most supported, which would indicate that trough's subsurface has 2 layers, which can

	be confirmed by the Zhurong rover o Ridges: ▪ Theories of formation mechanisms of ridges include inverted fluvial channels, linear dunes, lava tubes, igneous dikes and eskers ▪ Linar dune origin and inverted channel origin theories are unlikely ▪ Rover can help study the ridge's morphology and rocky type to determine if it has volcanic or glacial origins • Proposed a 5-layer model of the layers of rock of the rover landing region o Top layer A, consists of loose material that has relatively low temperatures during the night and might contain water-ice and/or CO2 ice o Right beneath layer A, layer B has more coarser and rocky materials o Layer C is made of material of thin sedimentary material, and has an avg thickness of about 100 m o Layer D has a thickness of 800 – 1000m o Layer E, the bottom most layer, a.k.a. the Noachian-aged basement • Summary o The purpose of further exploration by the rover is to answer these questions: ▪ How did the pitted cones form? ▪ How did graben-like troughs form? ▪ Evidence of ancient oceans? ▪ Evidence of mudflows? ▪ How are the layers of rocks in impact craters organized? ▪ Origin and nature of aeolian features? *Article contains links to data from HiRISE, CTX, THEMIS, MOLA, and JMARS at the end of the paper Article Summary: This article analyzes the terrain of Mars's southern Utopia Planitia, where China's Zhurong rover landed. Using satellite images and topographic data, the authors identify several geological layers formed by volcanic, icy, and wind-driven processes over billions of years. They highlight features such as cones, ridges, troughs, and possible ancient river or lake deposits that may reveal Mars's volcanic and water history. The study helps guide the rover exploration by identifying sites that could provide clues about past environmental and possibly habitable conditions on Mars.
Research Question/Problem/	Need: To identify important geological features and targets for in-situ

Need	exploration and analysis within the Zhurong landing region, to better understand the evolutional history of this region.
Important Figures	-  Impact crater with equator facing rim pits (indicated with red arrows) -  Largest impact crater within study region -  Shows longest Type 2 ridge found in the study region

- 

Shows many Type 1 ridge found in study region
- 

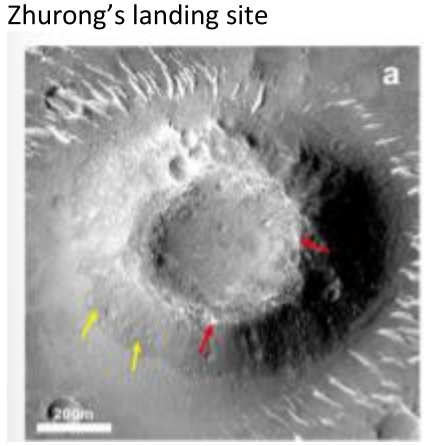
Nearest polygonal trough to Zhurong’s landing site
- 

Image of a cone in the study region

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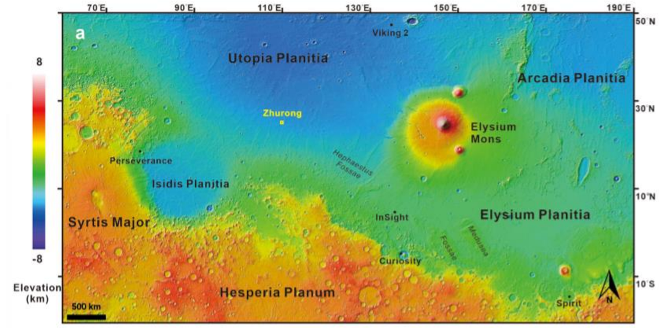
- 

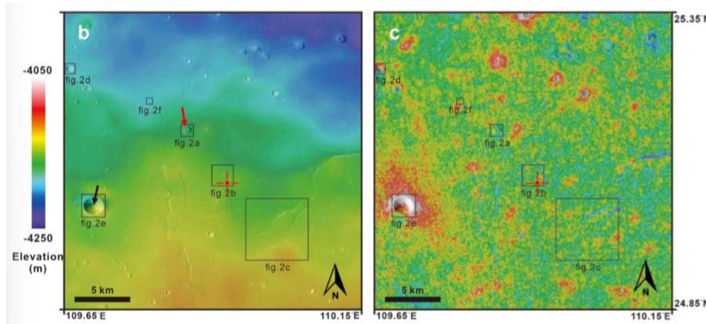
Topographical map of the surrounding area. The region being studied is indicated by the yellow square
- 

Fig b shows the topographical features of the study region, while Fig c shows the thermophysical properties of the surface material

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<td>VOCAB: (w/definition)</td>
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- **Topography:** the arrangement of natural and artificial features of an area
- **Geomorphological:** the study of the origins of topographical feature in a region
- **Effective Particle Size:** the particle size of the soil at which 10% of the soil is finer (in terms of weight)
- **Thermal Inertia:** A material's resistance to thermal change (materials with high thermal inertia take longer to heat up and cool down)
- **Ejecta Craters:** impact craters surrounded by debris that was blasted out during an impact event, or ejecta
- **Aeolian Bedforms:** land features created by the movement of wind-blown sediments, such as sand
- **Volcanic Rootless Construct:** a cone-like landform that forms without a direct connection to a volcanic vent; created when lava flows over water or ice which triggers steam explosions that build up cone shaped mounds

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<tr>
<td>Cited references to follow up on</td>
<td>

- Buczkowski, D. L., Seelos, K. D., & Cooke, M. L. (2012). Giant polygons and circular graben in western Utopia basin, Mars: Exploring possible formation mechanisms. Journal of Geophysical Research: Planets, 117, E08010. https://doi.org/10.1029/2011je003934

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	• Ruff, S. W., & Christensen, P. R. (2002). Bright and dark regions on Mars: Particle size and mineralogical characteristics based on Thermal Emission Spectrometer data. Journal of Geophysical Research, 107(E12), 2–1222. https://doi.org/10.1029/2001je001580
Follow up Questions	• How does the surface/terrain differ from different geological features? • Which path has the rover travel the least amount of distance while still allowing it to visit all the targeted areas? • What are some mobility issues that the rover might face along the way?

Article #12 Notes: Autonomous Extrication Control Method for Mars Rovers Based on Deep Learning

Source Title	Springer Nature Link
Source citation (APA Format)	Yang, W., Xing, Y., & Zhang, H. (2025). A method for autonomous intelligent extrication control of Mars rover based on deep reinforcement learning. In G. A. Tsihrintzis, M. N. Favorskaya, R. Kountcheva, & S. Patnaik (Eds.), *Advances in Computational Vision and Robotics: ICCVR 2024* (Learning and Analytics in Intelligent Systems), 47, 122–132. Springer. https://doi.org/10.1007/978-3-031-85952-6_12
Original URL	https://link.springer.com/chapter/10.1007/978-3-031-85952-6_12
Source type	Scientific Online Platform
Keywords	Mar Exploration; Deep Reinforcement Learning; Autonomous Intelligence; Extrication Control
#Tags	Mars, Terrain, Extrication

Summary of key points + notes (include methodology)	• Mar exploration is very important because it the most similar planet to Earth in the solar system
	• Six Mars rovers that have successfully conducted surface exploration of Mars: 5 from U.S., 1 from China
	• Mars has a weak atmosphere, heavily cratered topography and severe weather conditions
	• Currently rovers rely on visual tools to detect obstacles; however flat surfaces with hidden sinkholes are hard to visually detect
	• NASA's spirit rover constantly encountered situations where it sank too deeply into the soft Martian soil
	• Spirit required multiple extrication methods that took months to execute; after the 4th try it was unable to free itself, turning into a stationary observation platform
	• Opportunity also got stuck multiple times, ones of which was near Purgatory Dune, where it took it several weeks of effort to extract
	• **Extrication takes a long time and has a low success rate**
	• Design of autonomous and intelligent extrication method:
	  ○ Sensory info gathered by rover is passed to through a Feature encoder which gathers low-level informational features Aggregator component then transforms these low-level features into a fused feature vector
	  ○ Actor network then decodes these vectors, converting them into a probability distribution

	◦ The Critic network also decodes the same fused features, providing the output of the current evaluation of the rover's state + guides the Actor network in its optimization process ◦ The network then outputs the escape action with the highest probability of escape ◦ Martian rover's state information refers to measurable data regarding the vehicle's condition and its interaction with the environment ◦ **Intrinsic parameters of the rover** include rotational speeds of the drive motors of the wheels, rotational speed of the steering motors, steering angles of the wheels, velocity of the wheels, and overall velocity of the entire rover ◦ **Environment interaction information includes** wheel sinkage, slip ratio, and soil contact forces acting upon each wheel ◦ Decoded action candidates are transformed into a probability distribution for each action through the SoftMax function ◦ The speed command is designed with values of (-1, 0, 1), where 1 represents forward speed; 0 indicates stopping, and –1 signifies reverse speed. • Training of Extrication Intelligent Agent ◦ Training method is based on constraint satisfaction optimization strategies, which guarantees that decisions made are satisfactory and are feasible ◦ The regard system includes are sparse reward for successful extrication, providing large positive feedback to the agent when it completes a task, clearly defining its goal ◦ Intermediate awards are continuous and encourage the model to continuously attempt actions towards it objective ◦ Constraint rewards keep the model within the range of the Mars Rover according to engineering specifications ◦ In the Mars Rover sinkage situation, this setup assumes that one or more of the rover wheels are stuck in the sand, and the intelligence agent initiates the extrication process. Success is defined when all wheels are out of soft sand. • Training of Neural Network in Simulated Environment: ◦ Virtual simulation environment based on AGX Dynamics, which is capable of simulating sinkage and dynamics of Martian terrain ◦ Multiple simulation environments operate

	simultaneously, and each environment sends its current state (represented by s) to the policy network o Policy network makes decisions (a) based on current environmental states, and returns them to simulation environments for execution o The rewards (r) are generated by performing actions in the environment o The data collection module gathers all this information and forwards the state data to the value network, which evaluates the situation o Based on this data collected, the training algorithm employs a distributed multi-GPU training to update parameters of both the policy network and value network model o The iterative process continuously refines the models • Simulation Validating of Intelligent Self-Extrication Method: o After training the neural network model, it is integrated with a digital simulation software to validate the rover's effectiveness o In different sinking scenarios, as the number of simulated steps increases, the compaction of the sunken wheels gradually decreases from an initial value of 0.1m to less than 0.01m, gradually approaching zero once extrication is successful o Slip rate of the sunken wheels also gradually decreases to 0 as the rover successfully navigates out of the sand o Rover's velocity gradually returns to normal as it successfully exits the sandy area o Average extrication times were – 54.55s (compaction 1), 67.1s (compaction 2), 227.43s (compaction 3), 277.16s (compaction 4) and 404.22s (compaction 5) o **As complexity of sinking scenario increases, so does the average extrication time** ▪ However, this is still more efficient than manual operation o Proposed control method enables the rover to adjust the driving and turning speeds of its wheels independently when it is stuck Article Summary: This article focuses on creating a neural network that allows Mars rovers to autonomously extricate themselves from complex sinking situations in the Martian sand. Their methods involve using a hybrid reward system to ensure that the mechanism strives to complete its given task. Through deep reinforcement learning, they were able to calculate the wheel speeds and decide the best way to get a rover out of an embedding situation. They simulated the rover in 5 different

sinking scenarios, demonstrating that the neural network is successful in many different situations. This is further supported by the fact that as the vehicle extracts itself, the wheel sinkage approaches 0 and its slip rate declines. While the model is very effective in this simulation, further adjustments might need to be made to account for other sinking scenarios and real-world soil contact data. Additional constraints, such as the rover's power and the low-gravity environment on Mars, would need to be added to make the model more realistic.

Research Question/Problem/ Need

Problem: Current manual rover extrication methods are ineffective and have very low success rates.

Important Figures

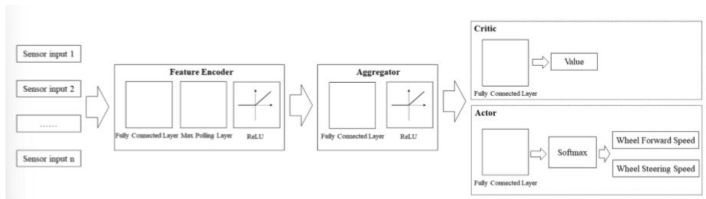
- 

Fig. 1. Neural network architecture for the extrication intelligent agent

- Table 1. Perception information

Perception information	Note
Wheel drive motor speed	6 wheel drive motor rotation speeds, measurable
Wheel steering motor speed	6 wheel steering motor speeds, measurable
Wheel steering angle	6 wheel steering angles, measurable
Wheel speed	6 wheel speeds, computable
Rover velocity	Vehicle body speed, measurable
Wheel compression	6 wheel sinkage depths, measurable
Wheel slip rate	6 wheel slip ratios, estimate
Wheel force	6 wheel-soil contact forces, measurable

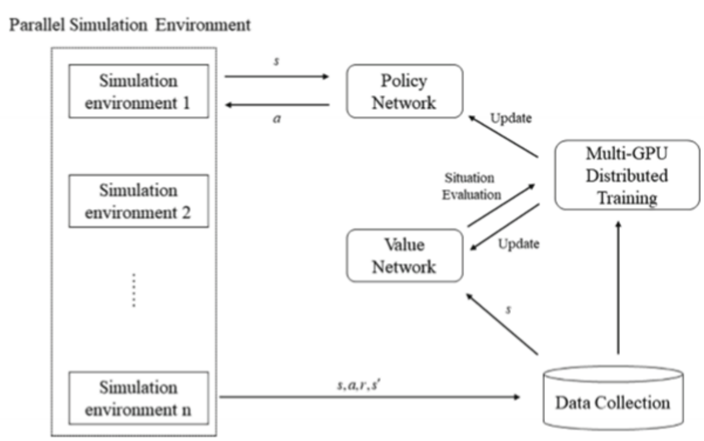
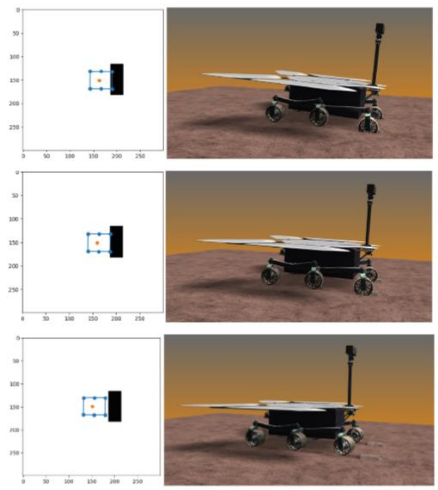
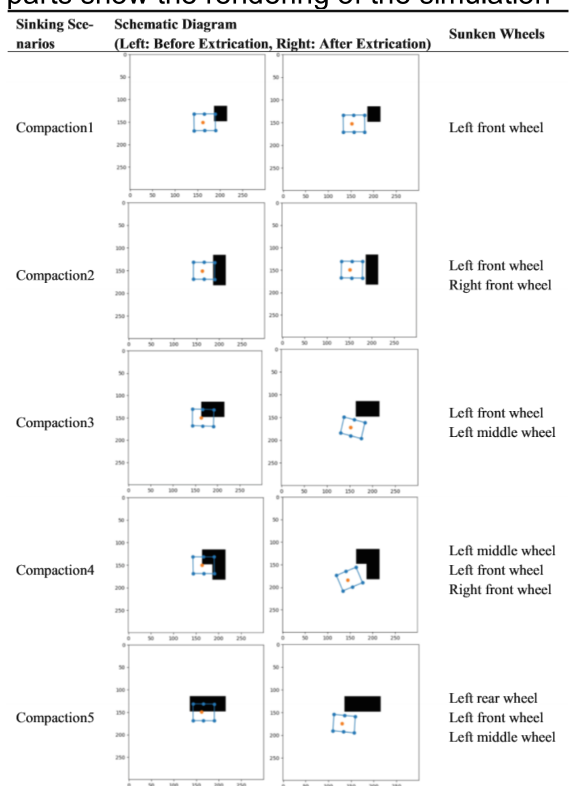
- 

Fig. 2. Agent training process



- **Fig. 3.** Simulation of Mars Rover escaping from sinkage
  The left side shows a schematic diagram of the rover's 6 wheels and the center of its body, with black area showing the region where sinkage might occur; the right parts show the rendering of the simulation



Sinking Scenarios	Schematic Diagram (Left: Before Extrication, Right: After Extrication)	Sunken Wheels
Compaction1		Left front wheel
Compaction2		Left front wheel Right front wheel
Compaction3		Left front wheel Left middle wheel
Compaction4		Left middle wheel Left front wheel Right front wheel
Compaction5		Left rear wheel Left front wheel Left middle wheel

- All 5 different sinking scenarios that the rover was tested on, and it successfully extracted itself from all of them

VOCAB: (w/definition)

- **Low-level informational features:** basic/granular foundational elements of the data; in this case it could be

	characteristics such as surface roughness, height variation, etc. • **Fused feature vector:** a single, unified representation created by combining multiple sets of vectors (e.x. from different sensors)
Cited references to follow up on	• Arvidson, R. E., Ashley, J. W., Bell III, J. F., Chojnacki, M., Cohen, J., Economou, T., Farrand, W. H., Fergason, R., Fleischer, I., & Geissler, P. (2011). Opportunity Mars Rover mission: Overview and selected results from Purgatory Ripple to traverses to Endeavour crater. *Journal of Geophysical Research: Planets*, 116, E00F15. https://doi.org/10.1029/2010JE003746 • Pan, D., Chen, Z., & Yuan, B.-F. (2022). Sinkage mechanism and extrication strategy of Mars rover. *Robot, 44*(1), 2-8.
Follow up Questions	- How can current rover sensors be modified to detect hidden sinkholes? - What is the average power a Mars rover has and how can this also be incorporated into the testing simulation? - Have they tested this in a physical rover yet?

Article #13 Notes: Push-pull Locomotion for Vehicle Extrication

Source Title	Science Direct
Source citation (APA Format)	Creager, C. M., Johnson, K. A., Plant, M., Moreland, S. J., & Skonieczny, K. (2014). Push–pull locomotion for vehicle extrication (NASA/TM-2014-218431). *NASA Glenn Research Center*. https://www-robotics.jpl.nasa.gov/media/documents/JoT%20final%20-%20push-pull%20locomotion%20for%20extrication.pdf
Original URL	https://www-robotics.jpl.nasa.gov/media/documents/JoT%20final%20-%20push-pull%20locomotion%20for%20extrication.pdf
Source type	Scientific Journal
Keywords	Mobility; Articulation; Extrication; Sinkage; Entrapment; Locomotion; Thrust; Wheel Slip
#Tags	Extrication, Mars

Summary of key points + notes (include methodology)	• Situations where a vehicle could potentially become entrapped can be difficult to assess
	• Drivers of the Spirit rover would assess its wheel slip by taking pictures of the rover's tread patterns on the soft Martian sand
	• Adding additional degrees of freedom to a robot helps it traverse difficult terrain and extricate itself from difficult situations
	• **Proposed solution is similar to the MoonCrab rover**
	• Push-pull locomotion:
	    ○ Thrust is generated by keeping a portion of the vehicle stationary, while moving the other part to a separate location (kind of like an inchworm)
	    ○ The previously stationary part is then repositioned to meet the previously moving part
	    ○ This alternating process then continues resulting in movement of the vehicle
	    ○ Walking is like push-pull locomotion, but the system designs for it typically more complex
	    ○ This paper focuses on the inch-worming method that propels itself forward using a combination of rolling wheels and vehicle articulation
	    ○ The Scarab roving vehicle from Carnegie Mellon University can both move by rolling and inching. Each wheel is attached to the end of an arm that extends out from the center of the chassis to a shoulder joint

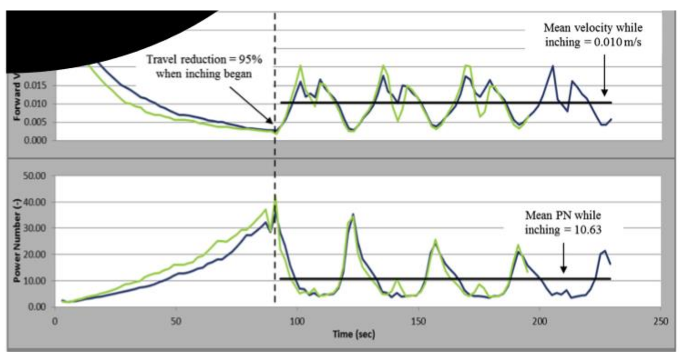
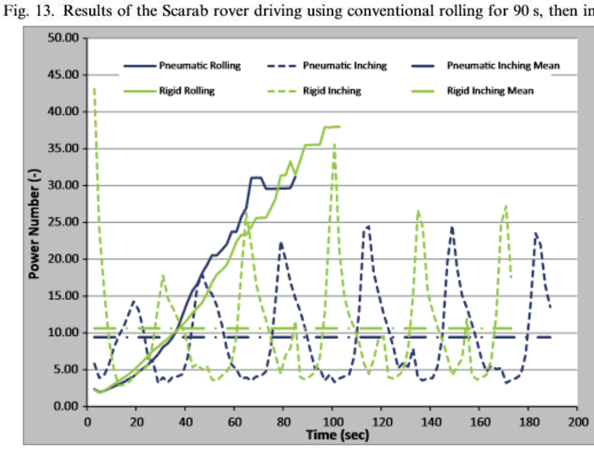
- First the rear wheels are held in place as the front wheels are driven forward, causing the wheelbase to increase
- According to (Czako et al., 1963), the trust generated by the stationary wheels is transferred to the moving wheels, allowing them to better overcome the resistance on the moving axle
- Additionally stationary wheels wouldn't have rolling resistance, so the **overall resistance of the vehicle as a whole has decreased, while keeping thrust the same**.
  - This allows this mechanism to generate more tractive force than a purely rolling vehicle

- Drawbar pull tests:
  - Compared the tractive forces of inching and rolling
  - Scarab rover was tested on a lunar simulant testbed, with a drawbar pull force apparatus applying a certain amount of force in the opposite direction of the rover's travel
  - For both the wheeled and inchworm motion, compliant and rigid tires were tested with multiple levels of drawbar pull
  - With pneumatic tires, inching locomotion could generate 37% of the rover's weight in drawbar pull, while rolling could only generate 27%
  - With rigid tires, pull force was 33% for inching and 25% for rolling
  - **Shows that deformable tires improve drawbar pull force (a.k.a. net tractive force)**
  - Drawbar pull/net tractive force is equal to the thrust generated by the wheels – rolling resistance
    - Since inching required less rolling, it could result in a higher net traction
  - Measured how much effect rolling resistance has on typical wheels, a similar wheel as used in the drawbar pull test, was tested to see the maximum pulling force (or rolling resistance) it could handle
    - Max rolling resistance was 5% of the vehicle's weight
    - Also, each axle would account for half of that resistance, so rolling resistance of each axle would be approximately 2.5% of the vehicle weight
- Soil response Beneath the Wheels:
  - The Soil Optical Flow Technique (SOFT) developed at Carnegie Mellon helps us see the motion of soil beneath a wheel by positioning a wheel in a soil tank against a clear glass wall so that the soil beneath the wheel can be viewed
  - Glass wall was determined to have negligible effect on the soil's response to the wheel
  - Wheel was mounted in such a way that it had free motion

	in the vertical direction (Z-axis) ○ Simulated wheel slip by controlling both the carriage velocity and rotational speed of the wheels ○ High resolution images of the soil beneath the wheel were taken ○ 2 cases were studied to better understand traction in inching versus rolling mechanism ▪ 1. Wheel and carriage were driven at speeds that produced a significant amount of slippage; to simulate conditions where drawbar pull force was close to the vehicle's maximum pull force for a wheel and weight • In the top halves of Fig 3 and 4, soil particles moved at an even rate along the profile of the wheel • Soil appeared to follow the edges of the wheel, moving with downwards components at the leading edge and upwards components at the trailing edge • This soil response is defined as "grip failure" ▪ 2. Wheel was braked while carriage was moved, simulating the stationary wheel in the inching mechanism • Velocity and directional response shown in bottom half of Fig 3 and 4 • Larger mass of soil was relocated when rolling • Instead of following the edge of the wheel, soil was pushed opposite to the direction of travel • Less vertical displacement of soil in these conditions. This response is defined as "ground failure" ○ Most soil displacement occurred in front of or behind the wheel in towing method, while with rolling wheel, most of the soil was engaged below the wheel ▪ Displacement of the soil below the wheel could be a contributing factor to the sinkage • Extrication Testing in NASA GRC Test Bed ○ Testing done in the Sink Tank, which is built to simulate conditions under which most vehicles would get stuck ○ It was never able to trap the Scarab rover, even when the wheel was deeply buried ○ Later used **Fillite**, because it contains hollow alumina silica microspheres, making it a high sinkage material. Its low-specific gravity also adds to its high sinkage properties and

low bearing strength.
    - Low bulk density of this material allows us to simulate lower gravity's effect on soil, which is usually overlooked (as demonstrated in Study Demonstrating That Using Gravitational Offset to Prepare Extraterrestrial Mobility is Misleading) but is significantly important for extrication studies
  - Important to reset the terrain to its normal loosened state before each test
  - To ensure consistency of terrain resetting method, 6 similar tests were also run with the pneumatic tires
    - For each of these the front wheel sinkage, rear wheel sinkage and total forward distance traveled were measured
    - After driving for 80s, avg front wheel sinkage = 17.6 cm; avg rear wheel sinkage = 24.6 cm and avg forward distance traveled = 1.02m
  - No pattern of change from test to test, indicated that the preparation method was sufficient to produce consistent results
- Test Setup and procedures:
  - Broken up into 2 cases based on their starting conditions
    - 1) Started Scarab on untouched terrain, to investigate how push-pull can be used to avoid immobilization
      - Resulted in a sinkage of less than 15% of the tire radius
      - From this position the vehicle was rolled and inched until it either got stuck or successfully traversed the terrain
    - 2) Investigated how push-pull mechanisms would help extricate the rover after it got stuck
      - Rover was first normally driven, then inching method was initiated once rover was stuck
  - In both cases 2 different tires with varying stiffness but similar dimensions were used
- Results:
  - Travel reduction is defined as the reduction in the forward velocity of the vehicle (v actual) to a specific reference velocity (v ref)
    - $$\mathrm{TR} = \frac{v_{\mathrm{ref}} - v_{\mathrm{actual}}}{v_{\mathrm{ref}}} \times 100\%$$
  - Reference condition was the self-propelled case on hard ground with same tire load and rotational speed as in the Sink Tank, because it represents the most efficient driving condition

	▪ This was used to calculate travel reduction for both rolling and inching o Power number (PN) was used to determine power usage for both rolling and inching; where power (P) used by the vehicle is normalized to the vehicle weight (W) and forward velocity (v actual) ▪ $\mathrm{PN} = \frac{P}{W * v_{\mathrm{actual}}}$ ▪ Low PN means that the vehicle is making decent progress for the amount of power being used o Free starting condition: ▪ Fig. 8 and 9 indicate a lower sinkage for the inching mechanism for both pneumatics and rigid tires ▪ Fluctuations in inching data correspond to inching cycles ▪ Sinkage of inching vehicle is steady, showing that its sinkage does not get worse over time ▪ In the forward distance traveled test, for the first 90 – 100 sec, the Scarab rover drove further while rolling, however the vehicle's forward speed started to decrease as the wheels began to sink after 30 – 40 sec. ▪ Average forward velocity remains constant for the entire duration ▪ Inching generally consumes more power, however rolling only operated more efficiently until it sunk into the sand ▪ In the testbed is too shallow, the bottom of the bin confines the soil particles, allowing the wheels to get a firmer grip on the sand resulting in higher thrust o Trapped Starting Condition: ▪ Results in Fig. 13 were collected by first driving the rover using the conventional sinking method for 90s, then initiating the inching method. ▪ As rolling continued, sinkage increased a velocity approached 0, but as soon at the vehicle began inching, its sinkage decreased and forward velocity increased ▪ Avg velocity of rover remained constant as the vehicle inched ▪ Power number continuously increased while rolling, but then fluctuated to a lower avg when inching started Article Summary: The purpose of this article was to investigate the benefits of a push-

	pull/inching mechanism in planetary rovers and whether it allows the rover to traverse loose terrain more efficiently. This mechanism imitates the movement of an inchworm and has been proven to generate more traction than traditional rolling motion. First, both methods of locomotion were tested for their maximum drawbar pull force using an apparatus that generated a force in the direction opposite of the rover's direction of motion. Inching motion had a higher maximum drawbar pull force. Then, using the SOFT technique, the soil interaction beneath both types of locomotion methods was studied. Finally, both types of motion were tested on a testbed with the high sinkage material Fillite. Inching showed to have less sinkage and higher thrust than compared to traditional rolling. While inching may be less efficient on hard ground, it requires less energy on a high sinkage terrain than rolling. Inching was particularly useful in the case where the rover wheels were already stuck in the soil. The authors' recommendation is to use the push-pull motion as a secondary mode of operation in rovers.
Research Question/Problem/ Need	What are the benefits of a push-pull locomotion in the case that planetary rovers are embedded or in need of extrication compared to traditional rolling methods?
Important Figures	 - Fig. 13. Results of the Scarab rover driving using conventional rolling for 90 s, then inch-worming.  Fig. 12. Power number (total power consumed normalized by vehicle weight and velocity). -

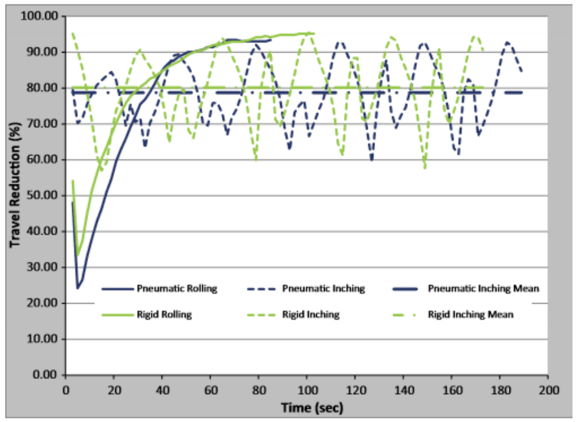


Fig. 11. Vehicle travel reduction as a function of time.

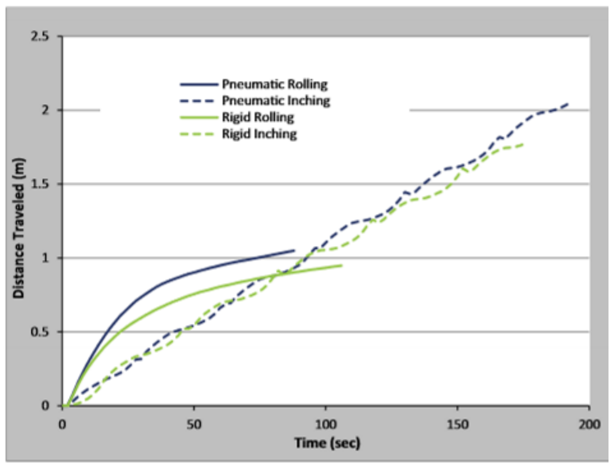


Fig. 10. Total distance traveled as a function of time.

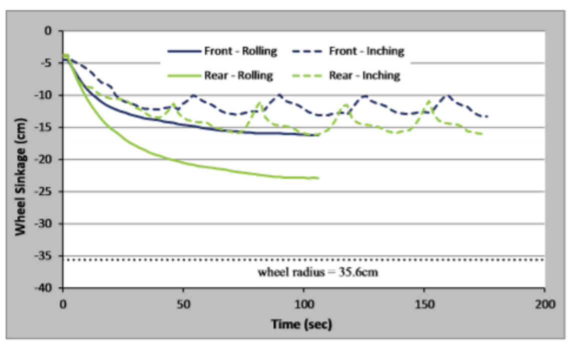
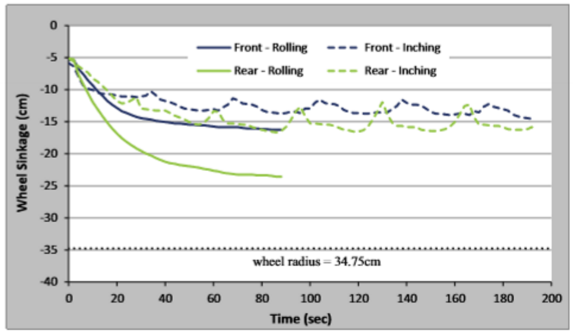
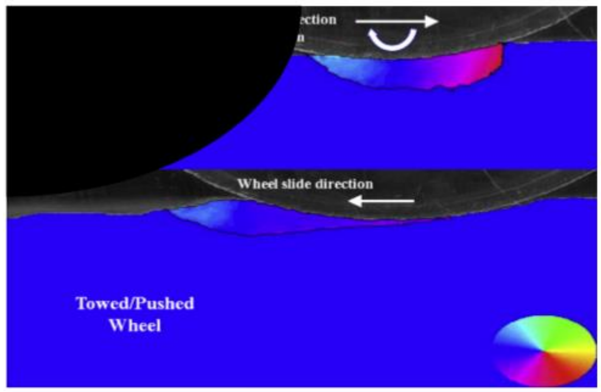
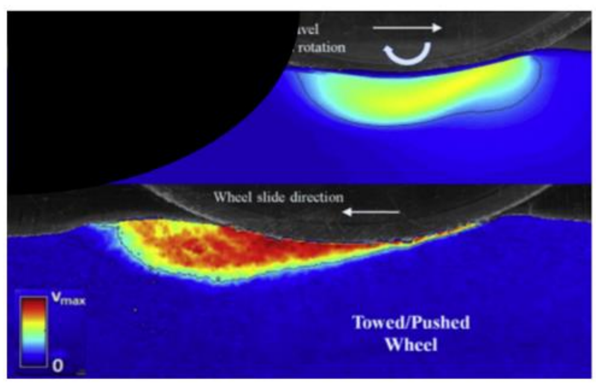


Fig. 9. Rigid tire sinkage (more negative represents deeper sinkage).

	 - Fig. 8. Pneumatic tire sinkage (more negative represents deeper sinkage).  - Fig. 4. Soil directional response to rolling wheel vs. pushed wheel; color indicates direction of soil particle velocity (Moreland et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)  - Fig. 3. Soil velocity response to rolling wheel vs. pushed wheel; color indicates relative magnitude of soil particle velocity (Moreland et al., 2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) -
VOCAB: (w/definition)	• **Wheelbase:** the distance from the center of the front and center of the rear wheels of a vehicle • **Drawbar:** a coupling mechanism used to connect a vehicle to a load or trailer • **Drawbar Pull:** towing force exerted by a vehicle at its drawbar for pulling purposes • **Pneumatic Tires:** tires that use air pressure to retain their shape

	and provide cushioning • **Rolling Resistance:** the forces that resists the rolling motion of a body on a surface • **Low Specific Gravity:** Indicates that the sand is less dense than water, causing a decrease in its overall strength • **Low Bearing Strength:** inability of a material to support maximum load per unit area without experiencing excessive settlement
Cited references to follow up on	• Creager, C., Moreland, S., Skonieczny, K., Johnson, K., Asnani, V., & Gilligan, R. (2012, April). Benefit of push–pull locomotion for planetary rover mobility. *In Proceedings of the ASCE Earth and Space Conference (Pasadena, CA)*. American Society of Civil Engineers. • Wettergreen, D., Moreland, S., Skonieczny, K., Jonak, D., Kohanbash, D., & Teza, J. (2010). Design and field experimentation of a prototype lunar prospector. The *International Journal of Robotics Research*, 29(12), 1550–1564. https://doi.org/10.1177/0278364910376446 • Czako, T. F., Janosi, Z. J., & Liston, R. A. (1963). *An analysis of multielement inching vehicles*. U.S. Army Tank-Automotive Center, Land Locomotion Laboratory • Bekker, M. G. (1960). Off-the-road locomotion. *University of Michigan Press*
Follow up Questions	• What aspects of the terrain make it difficult for rovers to assess the terrain? • While the inching method consumes more power when this method is scaled up to life-sized rovers? • Why does preventing the chassis from moving vertically reduce the amount of power needed? Could this be done by adding a linear slider system to the arm that connects the wheels to the chassis?

Article #14 Notes: RP-check: An Architecture for Spaceflight Command Sequence Validation

Source Title	IEEE.org
Source citation (APA Format)	Maimone, M. W., Maxwell, S., Biesiadecki, J. J., & Algermissen, S. (2018). RP-check: An architecture for spaceflight command sequence validation. In *2018 IEEE Aerospace Conference,* 1–10. IEEE. https://doi.org/10.1109/AERO.2018.8396785
Original URL	RP-check: An architecture for spaceflight command sequence validation | IEEE Conference Publication | IEEE Xplore
Source type	Scientific Journal
Keywords	Space vehicles; Tools; Sequential analysis; Space missions; Visualization; Planning; Databases
#Tags	Extrication

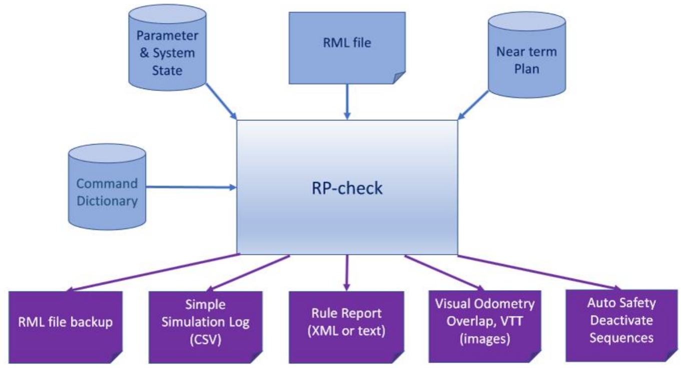
Summary of key points + notes (include methodology)	• Human operators plan each day of rover activities by creating **sequences of commands** that need to be review
	• Commands sent to Martian rovers are usually checked against a database of flight rules by hand or by an automated RP check
	• RP check is a rule-based checker system
	• **SeqGen** is the current command validator that checks every MSL (mars Science Laboratory) command sequence for rovers [11]
	• Takes a long time to assess command sequences, especially on busy days
	• The Surface Flight Software Simulation (SSIM) is used to perform a high-fidelity simulation of rover's mobility
	  ○ SSIM is very good at measuring rover position and attitude, but it doesn't check if rover's motion plan adheres with the Flight rule constraints
	• A tool called the remote Constraint Checker is used in addition to the SeqGen, along with RP-checks
	• General Architecture:
	  ○ RP check assesses how well the planned sequence of commands obeys flight rules and makes it easy to add new rules
	  ○ RP check tracks the tens of thousands of parameters associated with the 40+ motors onboard the rovers
	    ▪ However, it doesn't model anything about the surrounding terrain, nothing like the detailed simulation performed by SSIM

	▪ One of RP-check's design goals was to makes it capable of completing its analysis within 30sec, giving ground control more time to catch and fix errors earlier on
	▪ 100% code coverage over command sequences
	▪ If a conditional is found, it is treated as a normal statement, causing both branches of an anomalies to be evaluated
	▪ R-P check offers 2 different types of outputs: as a plain or as an XML
	▪ Has no knowledge of surrounding terrain, using only X, Y, Z positions and 6 degree-of-freedom of rovers
	▪ Purpose: NOT to resolve find positioning details because of the varying amount of SSIM
	  • Instead verifies when drives are planned in harsh environments
	• Rules Framework:
	  o Certain computations are known to be needed for more than one rule
	  o Having all the data readily available often simplifies the construction of new rules
	  o Each rule will typically loop independently through all planned commands, allowing multiple developers to work independently
	  o Examples of commands on pg. 5
	• Implementation:
	  o RP-check developers refer to command names only using constants that are generated from the Command Dictionary, ensuring that no typos or outdated references are made.
	  o Uses multiple helper programs has well, for example RP-checking uses Rayshade to generate images
	• Validation:
	  o Uses a unit test framework to ensure that any new changes don't break its capabilities
	  o Usually there was a higher number of negative test cases that positive test cases
	  o GNU Parallel is used to evaluate RP-check's performances over a thousand RML files in under 10 minutes
	  o Test logs are compared to previous test logs to ensure any unexpected changes will be detected earlier on
	• Usage During Mission Operations:
	  o RP-check can be run many times a day by rover planners
	  o Results of the MSL Flight Rule checks are posted every day to be reviewed by their team

	- As of 2017, RP-check has 242 explicit rules, can generate 534 different warnings and 542 error messages
	- RP-check has been used to validate flight commands for the rover, Curiosity, since 2012
	- It has also been used to generate flight sequences
	- Rover planners create a single "backbone" command sequences for periods of mobility of rovers
	    ▪ A safety deactivate sequence is also constructed for each backbone command
	    ▪ From 2004-2016, human rover planners had to construct safety deactivate sequences themselves
	    ▪ In 2016 RP-check was used to construct these sequences on its own
	- RP-check is becoming an integral part in response to Incident Surprise Anomaly Reports
	- Replaces the increasing patchwork of rules that must be checked by hand and process that must be followed by humans that get tired
	- Allows rover planners to make, test, and releases changes quickly, while also minimizing the repetition of past mistakes
	- Methods of Improving this model in the future:
	    ▪ Parallel processing of rules
	    ▪ Modify terrain modeling to account for situations where the terrain is slippery
	    ▪ Current visual odometry doesn't account for features that aren't visible to the rover operators and assumes the world is flat
	Article Summary:
	This paper discusses RP-check, a software developed at the Jet Propulsion Laboratory for verifying and validating spacecraft command sequences used in Mars Rover operations. Unlike traditional mission verification techniques that involve the rover planning team to manually check flight sequences, RP-check performs checks against hundreds of flight rules in under 30 seconds. It helps ensure that rover activities comply with operational constraints while allowing rover planners to continuously refine and test their plans throughout the day. The tool design emphasizes speed, modular rule integration, and ease of updates, making it essential for daily Mars Science Laboratory operations.

Research Question/Problem/ Need	How can rover planning teams reliably validate rover command sequences to ensure they follow flight rules and prevent operational errors?

Important Figures



-
- Examples Flight Commands:

Field	Description
Arm	
ARM_IN_CONTACT	Boolean true when the arm is expected to be in contact with terrain
ARM_OVERDRIVE	Amount of overdrive used during arm placement (meters)
ARM_TARGET_DIST	Distance to/beyond the current Arm Target (meters)
ARM_TOOL	Current Arm Tool
ARM_TOOL_DESC	Description of command that most recently set the Arm Tool
MAHLI Imager	
MAHLI_OPEN	Boolean true when MAHLI cover is open
MAHLI_OPEN_DESC	Description of command that opened MAHLI
MAHLI_OPEN_ELT	Command that opened MAHLI
DURATION	Coarse estimate of duration of this command (details only for imaging)
ACCUMULATED_DURATION	Coarse estimate of overall command durations
Drill	
BIT_IN_ROCK_ELT	Command expected to have placed the drill in contact
DRILL_STOW_DESC	Description of command that stowed the drill
DRILL_FEED_POS_MM	Drill Feed location post-command (millimeters)
DRILL_FEED_POS_MM_WAS	Drill Feed location pre-command (millimeters)
PRELOAD_N	Applied Preload Force (Newtons)
PRELOAD_PRELOADED	Boolean true when this command preloaded the arm
PRELOAD_UNLOADED	Boolean true when this command unloaded the arm
BATTLE_SHORT_DESC	Description of command that enabled Battle Short
PERCUSS_OR_RAMP	Boolean true when this command runs Percussion
Dust Removal Tool	
DRT_ACTIVE_IN_THIS_CMD_ELT	Boolean true when DRT active
DRT_RUNNING_ELT	Command that turned the DRT on
DRT_TURNED_ON_HERE	Boolean true when this command turns the DRT on
Inlet Covers	
IIC_OPEN	Mapping from Inlet Cover name to Description of Open command (if open)
Basic Driving	
SIMPLE_SIM_DELTA_H	Heading change expected from this command (radians)
SIMPLE_SIM_DIST	Distance driven by this command (meters)
SIMPLE_SIM_START_H	Pre-command Initial Heading (radians)
SIMPLE_SIM_START_X	Pre-command Initial Site Frame X position (meters)
SIMPLE_SIM_START_Y	Pre-command Initial Site Frame Y position (meters)
SIMPLE_SIM_START_VO_AZ	Pre-command Visual Odometry Azimuth angle (RNAV radians)
SIMPLE_SIM_START_VO_EL	Pre-command Visual Odometry Elevation angle (RNAV radians)
SIMPLE_SIM_H	Post-command Current Heading (radians)
SIMPLE_SIM_X	Post-command Current Site Frame X position (meters)
SIMPLE_SIM_Y	Post-command Current Site Frame Y position (meters)
SIMPLE_SIM_VO_AZ	Post-command Visual Odometry Azimuth angle (RNAV radians)
SIMPLE_SIM_VO_EL	Post-command Visual Odometry Elevation angle (RNAV radians)
Detailed Driving	
DOES_VO	Does this command perform a Visual Odometry Update
NAV_GOAL	Current Navigation Goal X, Y with Frame, Frame Index
VTT_TARGET	Current Visual Target Tracking X, Y, Z with Frame, Frame Index
DRIVING	Boolean true when this command could cause motion
TRCTL	Boolean true when Traction Control is enabled
STEERS	Boolean true if this command could steer the wheels
STEER_DESC	Description of most recent steering command
STEER_LF	Current LF steering position (radians)
STEER_RF	Current RF steering position (radians)
STEER_RR	Current RR steering position (radians)
STEER_LR	Current LR steering position (radians)
Internals	
NOSTACK_PARALLELS	List of sequences that might be running in parallel
COND_INSIDE	Conditional nesting depth count
PLAN_SOL	Sol on which this command will execute
STACK_DEPTH	Sequence nesting depth count
MOT_15000	Boolean true when this sequence was run without being cleaned up yet
MOT_15002	Boolean true when this sequence was run without being cleaned up yet

VOCAB: (w/definition)

- **Code Coverage:** a metric used in software testing to measure the extent to which the source code of a program is executed during testing
- **Uplink:** a connection that transmits data from a local network (LAN) to a wide area network (WAN)
- **Scalar Parameters:** a single value parameter, as opposed to a vector or matrix

	• **Unit Test Framework:** a set of tools, libraries, and convections that helps developer write and run automated tests for the small, isolated pieces of their code • **Visual Odometry:** technique used in computer vision to determine the position and orientation of a robot by analyzing camera images
Cited references to follow up on	• Biesiadecki, J. J., Baumgartner, E. T., Bonitz, R. G., Cooper, B. K., Hartman, F. R., Leger, P. C., Maimone, M. W., Maxwell, S. A., Trebi-Ollenu, A., Tunstel, E. W., & Wright, J. R. (2005, October). Mars Exploration Rover surface operations: Driving Opportunity at Meridiani Planum. In *Proceedings of the IEEE Conference on Systems, Man and Cybernetics* (pp. 1823–1830). The Big Island, HI, United States. • Leger, C., Trebi-Ollenu, A., Wright, J., Maxwell, S., Bonitz, B., Biesiadecki, J., Hartman, F., Cooper, B., Baumgartner, E., & Maimone, M. (2005, October). Mars Exploration Rover surface operations: Driving Spirit at Gusev Crater. In *Proceedings of the IEEE Conference on Systems, Man and Cybernetics* (pp. 1815–1822). The Big Island, HI, United States. • Patrikalakis, A., & O'Reilly, T. (2013, October). Advances in discrete-event simulation for MSL command validation. In *Proceedings of the IEEE/ACM International Symposium on Distributed Simulation and Real Time Applications*. Delft, Netherlands. • **Look for MSL database of flight rules**
Follow up Questions	• Could RP-check be adapted for more complex missions, such as AI driven spacecraft or launch vehicles? • How can the limitations of this model be modified to improve the accuracy of the validation system • How can this validation system be applied to systems of Earth, such as robots and drones?

Article #15 Notes: Autonomous Snake-Like Robot with Motion Planning Capabilities for Exploration of Icy Worlds

Source Title	Science Direct
Source citation (APA Format)	Vaquero, T. S., Daddi, G., Thakker, R., Paton, M., Jasour, A., Strub, M. P., Swan, R. M., Royce, R., Gildner, M., Tosi, P., Veismann, M., Gavrilov, P., Marteau, E., Bowkett, J., Loret de Mola Lemus, D., Nakka, Y., Hockman, B., Orekhov, A., Hasseler, T. D., … Ono, M. (2024). EELS: Autonomous snake-like robot with task and motion planning capabilities for ice world exploration. *Science Robotics*, *9*(90), eadh8332. https://doi.org/10.1126/scirobotics.adh8332
Original URL	EELS: Autonomous snake-like robot with task and motion planning capabilities for ice world exploration | Science Robotics
Source type	Scientific Journal
Keywords	Location awareness; Sea surface; Uncertainty; Torque; Shape control; Saturn; Snake robots
#Tags	Locomotion

Summary of key points + notes (include methodology)	• Icy moons of gas giant planets are of interest to astronomers because of the evidence suggesting they have sub-surface oceans (particularly Enceladus)
	• Plumes ejected from hydrothermal vents and geysers could have some biosignatures that may only be detected by direct samples
	• Prior knowledge of Enceladus's surface mainly comes from the Cassini mission, so a robotic explorer needs to be extremely adaptable under challenging conditions
	• Needs to be able to navigate at both surface and subsurface levels
	• Robot needs to be autonomous, adaptive and resilient to successfully execute mission
	• The EELS Project:
	    ○ Snake-like autonomous robot, with large active scales, that can conduct both surface and subsurface level exploration and overcome obstacles such as fluidized media, maze-like environments, and liquids.
	    ○ **Thermal Ice Drilling** is the primary approach to similar missions; however, it is inefficient due to the heat lost

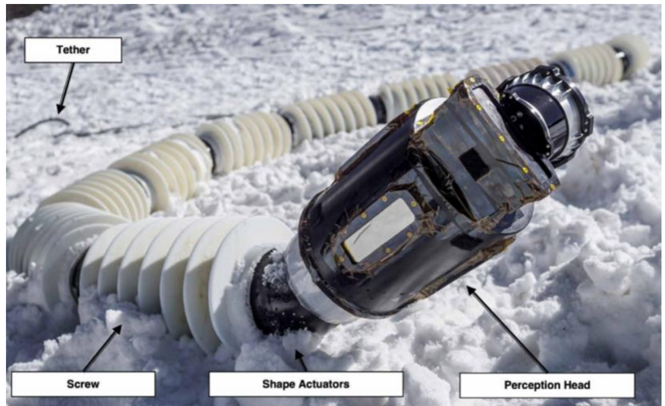
through the probe's sidewalls
- Another approach is through having robots capable of climbing down vent systems to traverse the rough, icy terrain
- EELS uses a pathway to a subglacial ocean to use the ice as terrain over which to move rather than a medium to move through
- 9 essential abilities needed for EELS:
  - Proprioceptive control (to interact with icy surface)
  - Gait/motion control
  - Exteroceptive perception (to gather geometric info of local environment)
  - Continuous motion planning (so robot can find the best path in any situation)
  - Global localization (to help map location in a global coordinate)
  - Global locomotion planning (to sync path and gait pattern)
  - Sensing (ex sampling, sensor deployment, etc.)
  - Planning execution of high-level mobility, science and engineering activities
  - Effective failure responses
  - Risk management (to ensure mission is executed within the specified risk thresholds)
- High uncertainty of terrain and low communication speeds between ground control and the robot led to the requirement of a system-level task and motion planner
- Characteristics of a good system-level planner:
  - Capable of inferring consequences of making a decision based on prior experiences
  - Allow system to adjust behaviors based on the risk the action poses to the mission

- Systems Architecture Overview (Hardware):
  - Traditional snake-like robot skins use shape actuators to create anisotropic skin friction; however, EELS uses an active skin **propulsion method using screws and tracks**
  - This allows EELS to have larger scales allowing it to carry heavier payloads and be more energy efficient
  - EELS is 10 units long, 4m in length and 100kgs
  - Each unit has 3 actuators: 2 to change robot shape and 1 to activate the "skin"
  - **Active skin propulsion** is done by the counterrotating screws attached to each module, which allows

	movement but also keeps the actuators in a quasi-static regime overall operation
	  ◦ Electrical power is housed in the robot's terminal (final) segment
	  ◦ The head segment has many sensors (light detector, LiDAR, stereo cameras, barometer etc.)
	    ▪ Also, can emit light to allow vision in dark enclosed environments
	• Software:
	  ◦ Goal-oriented autonomy
	  ◦ Risk awareness
	  ◦ Proprioceptive estimation module so that robot is aware about its internal state and position
	  ◦ Exteroceptive module infers the robot's pose and builds a map of the environment around it
	  ◦ Controller are organized in hierarchical way; at the top is the mission-level goals while at the bottom is the low-level hardware commands
	  ◦ Shape-screw control is controlled by a set of controllers that consider the desired path, desired controller and the output desired for the joint angle and screw velocity
	  ◦ Task and motion planning module receives goals from its operators in the form of constraints and plans a series of behaviors accordingly
	    ▪ Behaviors produce smaller goals for the low-level controllers
	• Surface Locomotion Strategies:
	  ◦ Main locomotion strategy is inspired by multiagent autonomy, decouples shape and screw-based locomotion
	  ◦ Hardware modules are controlled in a way that they follow the path made by the head segment
	  ◦ Robot can move holonomicaly by have each screw be at different velocities
	  ◦ Robot could also repeatedly vary its shape over blocks of time and generate thrust by simulating a sidewinding motion
	• Surface Locomotion Performance:
	  ◦ Robot tested on sand terrain at JPL's Mars Yard and snow terrain in CA
	  ◦ Test performed on flat ground, slopes and with obstacles
	  ◦ Tested on terrain with both consolidated and unconsolidated sand and snow
	  ◦ Leader-follower and shape-based gaits were tested
	  ◦ Exteroceptive and proprioceptive control were

	effective for both locomotion methods
	  - Screw-based motion was best for leader-follower gait
	  - **Shape-based gait was best for when the robot got stuck in situations that would have immobilized traditional rovers**
	  - Shape-based locomotion worked well for unconsolidated terrain, such as fine loose sand
	• Motion Planning Performance:
	  - The planning system's structure prioritized reasoning over uncertainity, allowing the robot to operate even in the presence of exteroceptive failures
	  - Compared an open loop behavior (where the robot's exteroceptive module was not scanning the environment) to their risk-aware planner during the physical tests on the test field
	    - **Results:** planning tasks along with the robot's motion give a safer plan for robot's movement
	  - Risk-aware policy worked better because it operated in an open-loop but while gaining new information through its sensors and planning when uncertainty was too much
	• Limitations:
	  - More work needed on autonomously matching the selection of the gait to the terrain conditions
	  - Transition between surface and subsurface exploration and integrating both components into the current design need to be researched more
	• Materials and Methods:
	  - Field tests are the best way to validate controls and assess the true performance of the robot
	  - Robot was exposed to 3 field locations and 1 lab setting
	  - Robot tested on inclines of 35 degrees
	  - Tests accounted for the distance covered and the robot's speed when determining its ability to traverse a rough terrain
	  - In the lab setting, robot was tested on a flat surface made of synthetic ice sheets
	    - Start, goal and obstacles were kept consistent
	    - Path tracking error, distance traveled, avg speed and #of manual interventions were used determine the robot's performance
	  - Inputs for the task and motion planning system:
	    - Operator specified goal in the form of waypoints that the robot needed to visit
	    - Map of the environment and the uncertainty

	model of the terrain ▪ Probability of violating a safety constraint ○ Generates a plan for the tasks based on these inputs and executes the plan by dispatching tasks and monitoring them ○ This model is different because it combines task and motion planning to account specifically for risk and uncertainty when finding the most optimal path ○ The task and motion planner's lab tests were conducted with constant start and end (goal) positions ○ Further iterations of the risk estimation, failure detection and recovery systems are needed, and they hope to combine surface and subsurface exploration mechanisms into this design in the future Article Summary: This paper talks about NASA's Exobiology Extant Life Surveyor (EELS) which is a snake-like autonomous robot designed to explore icy worlds such as Enceladus by traversing hazardous surfaces and vent systems to collect potential biosignatures. The authors describe the robot's hardware architecture (ten screw-based segments to generate thrust) and its software system, which integrates risk-aware task and motion planning for autonomous navigation under uncertainty. This robot design was tested in both laboratory and field tests in sand, snow, and ice terrains to assess locomotion performance. Simulation and hardware experiments were also conducted using a mixed-integer linear programming (MILP) approach to optimize navigation paths while managing risk and uncertainty. Results demonstrate EELS's adaptability across terrains and its ability to plan and replan trajectories autonomously despite sensor failures, an essential capability for future missions to extraterrestrial icy environments.
Research Question/Problem/ Need	How can an autonomous, risk-aware robotic system be designed to safely navigate and perform scientific exploration in the uncertain, extremely icy environments of planetary bodies such as Enceladus?

Important Figures	-  -  Overview of the test fields
VOCAB: (w/definition)	• **Proprioceptive:** relating to stimuli that are produced and perceived within an organism, especially those connected with the position and movement of the body • **Exteroceptive:** stimuli that are external to an organism • **Anisotropic:** having a physical property which has a different value when measured in different directions. • **Quasi Static:** a process of system that changes so slowly that it can be considered to be in a state of equilibrium • **Multiagent Autonomy:** the ability of multiple robots or agents to work together to achieve a common goal • **Decouples Shape:** the process of separating the dynamics and controls of different components or functionalities within a robotic system • **Holonomic System:** when a robot can move in any direction and configuration in space
Cited references to follow up on	• R. Thakker, M. Paton, M. P. Strub, M. Swan, G. Daddi, R. Royce, P. Tosi, M. Gildner, T. Vaquero, M. Veismann, P. Gavrilov, E. Marteau, J. Bowkett, D. Loret, Y. Nakka, B. Hockman, A. Orekhov, T. Hasseler, C. Leake, B. Nuernberger, P. Proença, W. Reid, W. Talbot, N. Georgiev, T. Pailevanian, A. Archanian, E. Ambrose, J. Jasper, R. Etheredge, C. Roman, D. Levine, K. Otsu, H. Melikyan, J. Nash, R. Rieber, K. Carpenter,

	A. Jain, L. Shiraishi, D. Pastor, S. Yearicks, M. Ingham, M. Robinson, A. Agha, M. Travers, H. Choset, J. Burdick, M. Ono, EELS: Towards autonomous mobility in extreme environments with a novel large-scale screw driven snake robot, in *IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS) (IEEE, 2023), pp. 9886–9893 • F. Richter, P. V. Gavrilov, H. M. Lam, A. Degani, M. C. Yip, ARCSnake: Reconfigurable snakelike robot with Archimedean screw propulsion for multi-domain mobility. *IEEE Trans. Robot*. 38, 797–809 (2022) • T. Dachlika, D. Zarrouk, Mechanics of locomotion of a double screw crawling robot. *Mech. Mach. Theory* 153, 104010 (2020). • K. Nagaoka, M. Otsuki, T. Kubota, S. Tanaka, Terramechanics-based propulsive characteristics of mobile robot driven by Archimedean screw mechanism on soft soil, in *IEEE/RSJ International Conference on Intelligent Robots and Systems* (IEEE, 2010), pp. 4946–4951 • M. Rashid, M. Yakub, S. Salim, N. Mamat, S. Putra, S. Roslan, Modeling of the in-pipe inspection robot: A comprehensive review. *Ocean Eng*. 203, 107206 (2020)
Follow up Questions	• How can this design be modified to support vertical motion? • How can the sidewinding motion be used to facilitate movement in liquid conditions (like conditions the robot would face in subsurface environments)? • How does the counteracting direction of the screw-like parts in the active skin allow the robot to move forward?

Article #16 Notes: A Shape-Changing Wheeling & Jumping Robot Using Tensegrity Wheels & Bistable Mechanism

Source Title	IEEE.org
Source citation (APA Format)	Spiegel, S., Sun, J., & Zhao, J. (2023). A shape-changing wheeling and jumping robot using tensegrity wheels and bistable mechanism. *IEEE/ASME Transactions on Mechatronics, 28*(4), 2073–2082. https://doi.org/10.1109/TMECH.2023.3276933
Original URL	https://ieeexplore.ieee.org/document/10144110
Source type	Scientific Journal
Keywords	Wheels; Robots; Mobile robots; Tail; Carbon; Gears; Shape
#Tags	Locomotion

Summary of key points + notes (include methodology)	• Robots with multiple modes of locomotion are better able to navigate complex terrain
	• Rolling function for these robots is enabled with the use of 2 tensegrity structure wheels that can collapse to increase the wheel's height while decreasing its width
	• Jumping function is enabled by a bistable mechanism that rapidly releases stored energy
	• Traditional round wheels struggle to overcome obstacles greater than the wheel's diameter
	    ○ A common approach to this issue, is to use whegs (wheel-like legs) to enhance the robot's ability to climb over obstacles
	• Othe methods of shape changing wheels include using linkages, origami, or centrifugal-driven mechanisms
	• Shape-changing wheel robots aren't effective at moving over taller objects – which is where jumping mechanisms come in
	    ○ Hybrid rolling and jumping robots usually have wheels or whegs that are rigid
	• Tensegrity structures are structures made of tension and pure axial loaded compression members, allowing this structure to deform and quickly absorb shocks
	• Robots with tensegrity wheels can:
	    ○ Climb over slope of 45-degree angles
	    ○ Overcome stair heights of 150mm
	    ○ Move at speeds up to 0.36m/s on both hard and soft

	terrain o Bistable mechanism allows robot to jump over 300m in height • The wheel design combines the benefits of whegs, shape-changing wheels and tensegrity structures, which allows the robot to o **Modify its shape** o **Absorb shocks** o **High payload to body weight ratio** o **Lightweight relative to its size** • Robot Design: 3 main parts – the tensegrity wheel, mechanism to collapse the wheels and mechanism to drive the wheels o Tensegrity Wheel: ▪ Icosahedron tensegrity structure, because it is symmetrical ▪ Structure is made of 6 rigid rods (made of carbon fiber, lightweight and stiff) and 4 elastic cables ▪ Two hubs on the ends of the wheels to ensure it can be both collapsed and driven • Interior hub is connected to the robot's body, while the exterior hub is like an anchor for when the cable collapses to decrease the wheel's width ▪ Endcaps were added to each rod's end to generate enough friction to propel the robot forward ▪ Rod's lengths can be customized, but they use a length of 130mm here ▪ Elastic cables are 3D printed and made from highly elastic TPU filament ▪ Rod endcaps are also 3D printed abrasion resistant TPU ▪ Wheel hubs are made up of the central hub, 3 short carbon fiber rods emanating from the central hub, and 3 compliant connectors connecting the carbon fiber rods to the rods of the tensegrity ▪ If tension in the elastic is too high, then collapsing the tensegrity structure would require a larger motor o Collapsing Mechanism: ▪ A cable-driven system with a nylon cable is used collapse the wheel ▪ One end of the cable is anchored to the

	exterior hub (however it can still rotate, allowing the wheel to collapse while rolling) ▪ Cable runs through the open center of the wheel then through the interior hub's center ▪ From here is router through the robot's body and into a pulley driven by a micro metal gear motor ▪ Pulley pulls the cable, causing the wheels to collapse from the icosahedron to a flat disk-like shape ▪ **Collapsing the wheel decreases the robot's total width but increases its ground clearance** ▪ For a rod length of 130mm, width decreases from 400-180mm, and ground clearance increases from 75 – 90 mm o Driving Mechanism: ▪ Both tensegrity wheels are driven by a pair of micro metal gear motors ▪ Each motor is connected to a 3D printed gear with a gear ratio of 3:1 to increase torque ▪ Robot moves forwards and backwards by turning both motors in the same direction and turns by spinning the motors in the opposite directions • Jumping Mechanism: o Robot uses bistable mechanism to store energy and quickly release it o This mechanism was chosen because it is lighter than compared to spring-based jumping mechanisms o Mechanism consists of a flexible plate, with 1 end attached to a passive joint and the other attached to an active rotational joint o The jumping foot attached to the plate is pushed against the ground during the jumping process o Plate starts at the position in state 1, active joint rotates the plate to store elastic potential energy o After it passes its critical position, the plate quickly snaps, releasing the stored energy and causing the jumping foot to rapidly push against the ground o Jumping foot is clamped over the fiber plate, allowing its angle relative to the plate to be adjusted so that the robot can jump at different angles • Body and Tail Design: o Robot body houses all electronics, motors and the bistable mechanism o 2 motors for driving the wheels are placed on the

	sides o 1 motor for collapsing the wheel is located at the rear o 2 motors for actuating the bistable mechanism are place at the front o Tail made of carbon fiber rod with a small passive wheel on the end ▪ Tail aids the robot is climbing up obstacles and slopes by acting as a compliant arm ▪ Also assists the robot's jumping function to ensure the robot doesn't flip/fall when at its peak height • Force Required to Collapse the Wheel: o Necessary to know when selecting the appropriate motor to collapse the wheel o When the rod length is fixed, the collapsing force depends on the elasticity of the cables o FEA was sued to analyze the force, due to the complex nature of the problem ▪ First experimentally found the force-displacement relationship for a single elastic cable (did this by stretching a cable to the length it would be on the expanded tensegrity – 83 mm; then doing the same with a released cable) ▪ Also, they performed these tests at the velocity the cables are usually stretched and relaxed at (0.85mm/s) o Using data from the single wheel, FEA is used to predict force-displacement when the entire wheel is collapsed o Validated simulation results by also experimentally gathering the force-displacement relationship for collapsing a wheel o Results show a large reduction in the required force a little over halfway through the collapsing process (because some members are applying a force in the direction of the collapse after some of the rods make contact) o Graph for simulated force has a similar shape to the experimental force and simulated force is 5% off from experimental results ▪ This could have happened due to minor discrepancies in the actual speed of the cables during the collapsing process o Based on the experimental results, at least 8N is required to collapse a wheel (16N for both wheels on the robot)

- Much more force will be required to collapse the wheel on rough surfaces, so a motor that can supply twice the minimum amount would be ideal

- Maximum Climbable Step Height with Expanded Wheels:
    - Obtained by looking at the wheel from the side of the wheel hubs
    - From this view, wheel looks like a hexagon, if connecting vertex to vertex
    - Calculations detailing how to find projected length and rod length on pg 2078
- Maximum Climbable Height with Collapsed Wheels:
    - In this configuration's 2-D shape, the length of the rod and end cap change to its original length

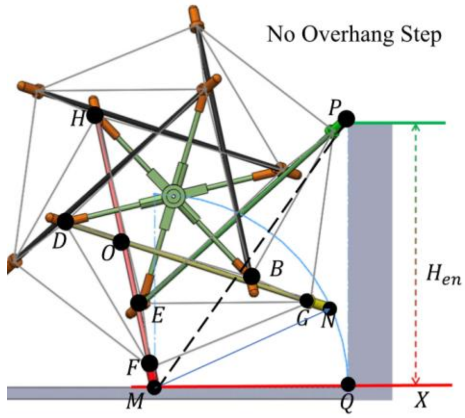
Experimental Results:

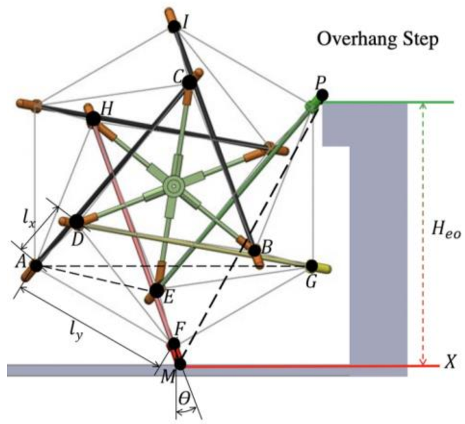
- Wheel Test: icosahedron shape results in a zig-zag pattern on the surface, but since both wheels are symmetric it results in the robot moving forward linearly
    - **Robot can move 86.6mm/step expanded and 99.6mm/step when collapsed**
- Jumping Height Test:
    - Robot requires a take-off angle to clear obstacle
    - Changed the foot's angle relative to the robot's body to test optimal jumping position (tried 50, 60, 65, and 70 degrees)
    - Tested on hard surface and analyzed motion using a video tracking software
    - 3 jumping tests conducted for each angle of the jumping foot
    - **Maximum jumping height when the jumping foot was at 65 degrees from robot's body**
    - **Robot can jump to height of 384mm, but maximum obstacle clearance height is 300mm due to jumping foot's length**
    - 2x the maximum step height achieved by collapsed wheels
- Inclined Slope Test:
    - Robot tested on variable angle degree slope made with thick foam with a high friction cabinet liner on it surface
    - Static friction coefficient was 0.78 between the wheel and the liner
    - Slope angle incrementally raised by 5 degrees until robot couldn't climb up further
    - **Ascends inclines up to 35 degrees without slippage**
    - **Maximum incline it could ascend was 45 degrees**
    - Without the high grip liner (coefficient of friction =

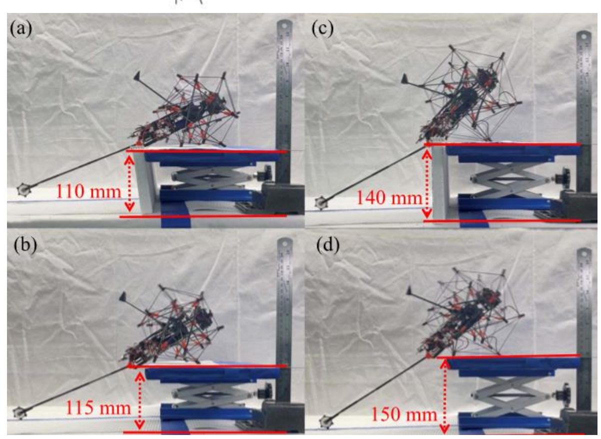
	0.57), it could only climb slopes of 40 degrees)
	• Maximum Climbable Step Height Test:
	  o Tested for both expanded and collapsed wheels, each for two cases with and without an overhang
	  o Placed robot in front of the obstacle, then it rolled forward until it encountered the step
	  o Step size was increase by 5mm after each test until the robot could no longer climb it
	• Field Experiments:
	  o Created an obstacle course to test the robot of different terrain features such as, rock piles, walls, loose pipes, narrow gaps, steps and ramps
	  o Also conducted payload testes by adding bottle filled with liquid to until robot could no longer move forward
	    ▪ Can carry 1222g, 4.9x its weight
	  o Test robot on gravel with avg grain size 2mm
	• Advantages of Design: Lightweight (17g, 6.8% of total robot weight), easy to assemble, shape changing ability, and good durability
	• Improvements:
	  o Robot may fall sideway, especially when jumping, due to thinness of wheels and two-wheel configuration (which can be solved by making it a 4-wheel config)
	  o FEA model used to predict collapsing forces, but an analytical model would be preferred
	  o Current robot is manually controlled, but could be integrated with cameras and GPS
	Article Summary:
	This article talks about a robot that can both roll and jump using tensegrity wheels and a bistable mechanism. The wheels, made from rods and elastic cables, can expand or collapse to adapt to different terrains, absorb shocks, and allow the robot to climb obstacles. The researchers designed and built the robot, then used finite element analysis (FEA) to model the force needed to collapse the wheels. They tested the wheel's performance through wheel, jumping, slope climbing, and outdoor experiments across sand, rocks, slopes, and snow. Results showed that the robot could shrink its width by over half its original, climb 150-mm steps, jump up to 300 mm, and carry nearly 5x its own weight. Overall, the study demonstrates how tensegrity-based, shape-changing designs can improve mobility and durability in robots for exploration and search-and-rescue missions.

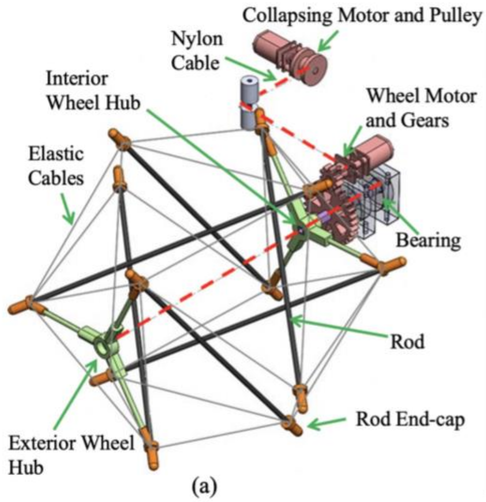
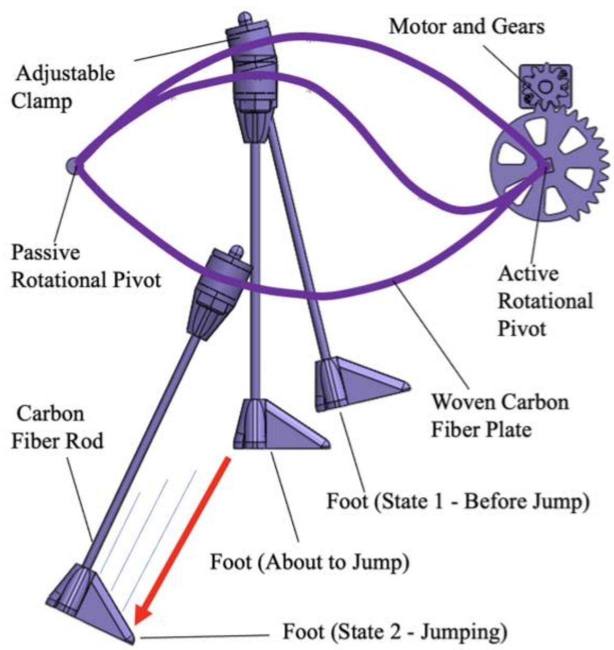
Research Question/Problem/ Need	How can tensegrity structures be used in shape-changing wheels to create an adaptable robot capable of both driving and jumping on challenging terrain?

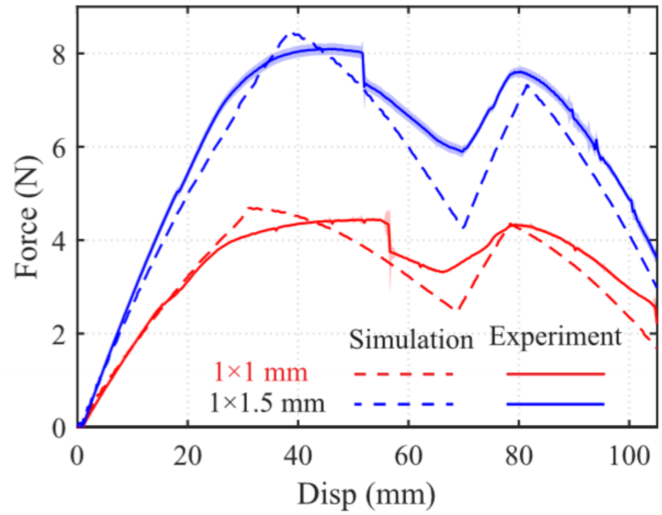
Important Figures

- 

- 

- 

	 - Collapsing Mechanism  - Bistable Jumping Mechanism

	 - Comparison of simulation and experimental results of the force-displacement relationship when collapsing the tensegrity wheel
VOCAB: (w/definition)	• **Icosahedron:** A polyhedron with 20 faces
Cited references to follow up on	• Y. She, C. J. Hurd, and H.-J. Su, "A transformable wheel robot with a passive leg," inProc. *IEEE/RSJ Int. Conf. Intell. Robots Syst.,* 2015, pp. 4165–4170 • D.-Y. Lee, S.-R. Kim, J.-S. Kim, J.-J. Park, and K.-J. Cho, "Origami wheel transformer: A variable-diameter wheel drive robot using an origami structure," *Soft Robot*., vol. 4, no. 2, pp. 163–180, 2017 • D.-Y. Lee, J.-K. Kim, C.-Y. Sohn, J.-M. Heo, and K.-J. Cho, "High-load capacity origami transformable wheel," *Sci. Robot.*, vol. 6, no. 53, 2021, Art. no. Eabe0201 • M. Shibata, F. Saijyo, and S. Hirai, "Crawling by body deformation of tensegrity structure robots," in *Proc. IEEE Int. Conf. Robot. Automat.*, 2009, pp. 4375–4380
Follow up Questions	• Why did the robot's distance per step decrease when the wheel expanded if expanding it results in a larger radius of the wheel? • Will it still have the same load capacity when subjected to larger loads? • Why didn't the researchers use a 4-wheel configuration in the first place?

Article #17 Notes: Compliance-Tuning Soft Inflatable Wheels for Robot Mobility on Various Terrains

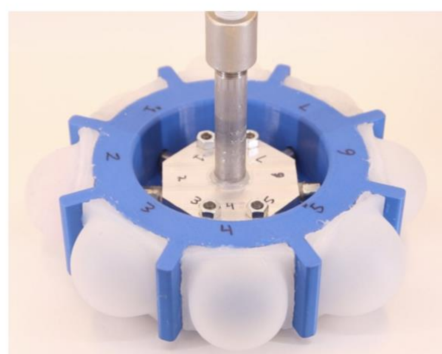
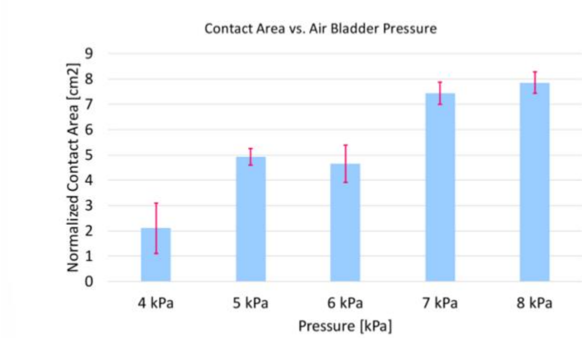
Source Title	IEEE.org
Source citation (APA Format)	Almusa, A., Galeza, R., Wang, M., & Majidi, C. (2020). Compliance-tuning soft inflatable wheels for robot mobility on various terrains. In *2020 3rd IEEE International Conference on Soft Robotics (RoboSoft),* 558–563. IEEE. 10.1109/RoboSoft48309.2020.9116017
Original URL	Compliance-Tuning Soft Inflatable Wheels for Robot Mobility on Various Terrains | IEEE Conference Publication | IEEE Xplore
Source type	Scientific Journal
Keywords	Wheels; Metals; Bladder; Soil; Soft robotics; Surface roughness; Rough surfaces; Mobile robots; Tuning
#Tags	Locomotion

Summary of key points + notes (include methodology)	• A wheel's mobility on a given terrain depends on its geometry and elasticity, so a vehicle traveling on a diverse variety of terrain would benefit from being able to alter these characteristics
	• Their design used soft elements to fill the space in between the grousers, to measure effects of variable compliance on different terrains
	• Design Overview:
	  ○ 8 molded elastomer chambers are placed between the grousers, powered with a system of pneumatic components
	  ○ Central hub of the wheel is an aluminum air pump that receives air from the wheel's hollow axle distributing it to the 8 bladders
	• Theoretical Model:
	  ○ Used FEA results to compare different bladder chamber designs to see which one has the best deformation behavior
	  ○ Used Ecoflex-0030 silicone for material when simulating
	  ○ Wheel-terrain interaction was modelled as the static normal force, and the contact area of the bladder on the terrain as a function of inflation
	  ○ Used static conditions at first to gain an initial understanding of the wheel's design and how it

	changes with inflation ○ Contact area of bladder helps distribute the load over a larger area, reducing the stress on the terrain ○ Wheel will experience less sinkage on soft terrain because the grousers now aren't carrying the complete weight of the wheel ○ Stress on terrain = Normal Force(N)/Contact area of bladder (A) $\sigma = N/A$ • Fabrication Method ○ Air bladders made by pouring silicone into 2 plastic molds ○ Silicone was then degassed and allowed to cure in a vacuum chamber at 80 degrees Celsius; then 2 pieces of each air bladder were attached with Smooth-On Sil-Poxy adhesive ○ Wheel's rim was 3D printed ○ Rim and hub were mechanically fastened while the rim and air bladders are bonded with adhesive ○ Urethane tubing is connected to each bladder, and pneumatic connections are sealed with Sil-Poxy • Experimental Set-Up ○ Experiments focused on measuring bladder contact area and its contact force on the sand as a function of the air pressure ○ Measuring contact area: ▪ Water-based dye applied to one of the bladders ▪ Bladder was inflated to a desired pressure then set vertically on a piece of grid paper, so that it would apply dye wherever it contacted the paper ▪ This was done for trials at pressures 4, 5, 6, 7 and 8 kPa ○ Measuring Ground Contact Force: ▪ Vertically oriented scale was placed against the circumference of the wheel ▪ Scale was zeroed at the point where no air pressure was applied ▪ Contact force displayed on the scale was recorded at pressures of 3, 4, 5, 6, 7, 8, and 9 kPa • These pressures were chosen because they were high enough to create contact force but low enough to prevent damaging the wheel • Slip Experimental Set-up:

	- Measured on a carousel like testbed that allowed the wheel to revolve around a central pivot over different terrains - Both the central motor and the motor driving the central pivot have encoders - Time is used to measure slip: less time required to complete a revolution indicates fewer slip incidents • Results: - Ground Contact: ▪ **Contact area with the ground increases with pressure** (Fig. 4) ▪ Fig 4. closely matches results from the simulation shown in Fig 5. ▪ Max contact area was at 8 kPa, which was approx. 8.5 cm^2 ▪ **Contact force between air bladder and ground also increases with air pressures** (Fig. 6) ▪ Discrepancies between the simulated and experimental results due to likely minor leakage in air bladders - Wheel Slip: ▪ Time per revolution was measured of the wheel was measured for both soft and rough soil and hard and smooth metal surfaces ▪ This was done at 3 inflation pressures: 0 kPa, 5kPa, and 8kPa ▪ **Time to complete a revolution decreased when the inflation pressure was increased on soil surface** ▪ **Revolution time increased with the inflation pressure on metallic surfaces** ▪ In soil surfaces, it was expected that the wheels would perform better because the padding effect of the soft surface prevented the air bladder from lifting the wheel of the ground. • Grousers still interact with the ground, while air bladder increase surface area while reducing stress on the terrain • Reduces sinkage of the grouser distributing the load over an area ▪ On metal surfaces, the grouser-only (0kPa) mode would exhibit more slippage • Heavy wheels would skid breifly each time it lands on the next grouser

	during a rotation ▪ **Number of slips was reduced with inflated wheels on sandy and obstacle terrain, but not the case for metallic surfaces** o Obstacle Climbing: ▪ Test was conducted on similar sandy terrain, with 4 equally spaced rocks around the carousel ▪ Time required increased by 20% when tested on obstacle terrain than compared to plain terrain • Difference in time is negligible when the bladders where inflated ▪ Addition of the bladder, allows the grouser to grip onto and propel itself over an obstacle without slipping, due to the conforming surface of the bladder o Slope Climbing: ▪ Testes performed on a smooth metal plate whose incline was gradually increased ▪ At 14.2 degrees the grouser only; mode was unable to continue climbing, while the inflated bladder was able to. • Conclusion: o Simulations and empirical studies were used to study the effect of air pressure on ground contact area and contact force o Contact area and force increase with air pressure o Inflating air bladders decreased the slip on sandy soil and rocky obstacles o Increased traction on both hard and soft surfaces when the bladders were inflated ▪ In metals the traction reduced the forward momentum of the wheels ▪ Inflating bladders helped wheels overcome obstacles that uninflated wheels could not o Future works include: ▪ Variation of wheel that are lighter and have higher air pressures, so that “lift-off” can be tested (when the rover is fully supported by air bladders instead of grousers) ▪ Made more useful on obstacles if each bladder was individually controllable ▪ Better modes of measurement could be used to measure wheel performance in these situations, other than wheel slip Article Summary:

	The article investigates an alternative, inflatable wheel design to investigate robot's mobility on sand, rock, and metallic surfaces. This design explores the addition of silicone air bladders between the wheel's grousers. Compliance in the wheel is adjusted by changing its air pressure. Increasing the wheel's air pressure also increases the wheel's contact area and normal force, reducing slip and improving traction of the vehicle. Their wheel design was tested using empirical observations and finite element analysis simulations. Experimental tests measured the contact area, contact force, slip events, obstacle traversal and slope climbing ability of the wheel. Both the simulation and experimental data gave very similar results, emphasizing the accuracy of the physical tests. Slight discrepancies between simulated and empirical data might have occurred due to air leakage. Results showed that inflated bladders increase the contact area of the wheel and the normal force while reducing slippage on sandy terrain and obstacles. Inflated wheels were also better at climbing slopes than uninflated grouser wheels. The result of this study suggests that variable compliance and pneumatic wheels can enhance robot mobility on a diverse set of terrain.
Research Question/Problem/ Need	To study the effects of inflatable soft wheels on deformable soil.
Important Figures	 - Fig. 1. Inflation state of a soft material integrated wheel. The space between the rigid wheel grousers is filled by inflatable air bladders.  Fig. 4. Contact area between the ground an air bladder at various air pressures. -

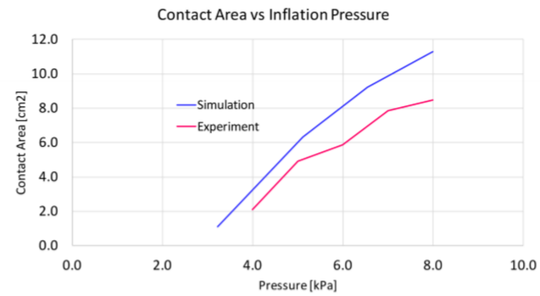


Fig. 5. Comparison of simulated and experimental results for ground contact area as a function of applied air pressure.

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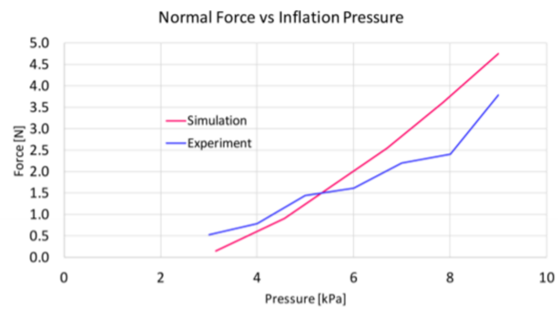

Fig. 6. Comparison of simulated and experimental results for ground contact force as a function of applied air pressure.

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TABLE II

REVOLUTION TIME FOR DIFFERENT SURFACES AND INFLATION PRESSURES.

	Time[s]	
Pressure[kPa]	Soil	Metal
0	28.247	20.122
5	26.982	21.828
8	26.130	21.770

-

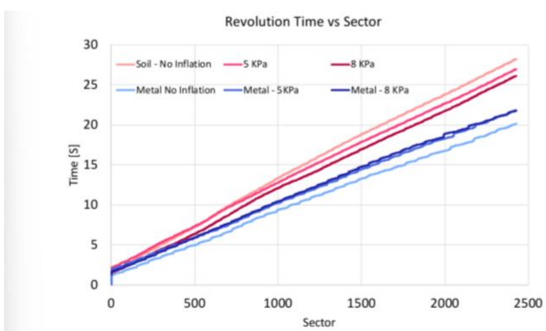

Fig. 7. Revolution time vs sector for different inflation pressures over soil and metal surfaces.

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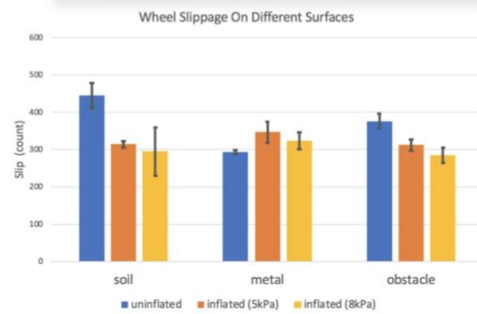
	 - Fig. 8. Grouser-bladder contact tread marks during inflation tests.  - Fig. 9. Comparison of number of slips occurred during sandy terrain test, smooth metal surface test, and obstacle test at three different wheel states: uninflated, inflated at 5 kPa and inflated at 8 kPa.
VOCAB: (w/definition)	• **Empirical:** based on observational experience
Cited references to follow up on	• G. Ishigami, M. Otsuki, T. Kubota, and K. Iagnemma, ‘Modeling of Flexible and Rigid Wheels for Exploration Rover on Rough Terrain’, in Proceedings of the 28th International Symposium on Space Technology and Science, 2011. • D. Lee, J. Koh, J. Kim, S. Kim and K. Cho, “Deformable-wheel robot based on soft Material” INT J PR ENG MAN-GT. vol. 14, no.8, pp. 1439-1445. Aug. 2013 • K. W. Wait, P. J. Jackson and L. S. Smoot, ”Self locomotion of a spherical rolling robot using a novel deformable pneumatic method,” 2010 IEEE International Conference on Robotics and Automation, Anchorage, AK, 2010, pp. 3757-3762. doi: 10.1109/ROBOT.2010.5509314
Follow up Questions	• Why was silicone in particular used to fabricate these wheels? • When they say increasing air pressure increases ground contact, are they simply referring to the fact that having the air bladders increases ground contact? (because I thought that decreased air pressure in already pneumatic tires helped the tire conform to its terrain). • How did they manufacture the pump to connect throught the axle of the wheel’s motor?

Article #18 Notes: Modeling of Flexible and Rigid Wheels for Exploration Rover on Rough Terrain

Source Title	Semantics Scholar.org
Source citation (APA Format)	Ishigami, G., Otsuki, M., Kubota, T., & Iagnemma, K. (2011). Modeling of flexible and rigid wheels for exploration rover on rough terrain. *In Proceedings of the 28th International Symposium on Space Technology and Science.* https://www.semanticscholar.org/paper/Modeling-of-Flexible-and-Rigid-Wheels-for-Rover-on-Ishigami-Otsuki/fef42aeec5da71d8811ec1fde8ed5b91d94bf5d8
Original URL	https://www.semanticscholar.org/paper/Modeling-of-Flexible-and-Rigid Wheels-for-Rover-on-Ishigami-Otsuki/fef42aeec5da71d8811ec1fde8ed5b91d94bf5d8
Source type	Academic Database
Keywords	Planetary Exploration Rover; Flexible wheel; Wheel contact model; and Terramechanics
#Tags	Locomotion, Terrain
Summary of key points + notes (include methodology)	• Martian planetary rovers, such as MER, Sojourner, and Curiosity, have metallic rigid wheels with multiple grousers • Need: While many models have been developed regarding rigid wheel and flexible wheel terrain interactions, an explicit model that can address both flexible and rigid wheels on deformable terrain has not yet been well studied • Discrete Element Method can be useful in analyzing flexible wheels on deformable terrain, even though it requires a lot of computational effort because the model consists of a large number of elements • Their model evaluates the traction performance of rigid and flexible wheels, while also calculating the wheel's deflection and sinkage based on stiffness • Their model divided that contact area of the wheel with the ground into 3 parts: Wheel front; wheel deflected (flat) section; and wheel rear section. • Stress distribution in each section is calculated based on the type of soil, how the wheel is moving, and pressure the wheel applies on the terrain due to its stiffness ○ This allows the model to be applicable for both flexible and rigid wheels • Traction performance of the wheel is based on wheel sinkage,

	drawbar pull, resistance torque, and traction efficiency
	• Wheel-Terrain Interaction Category:
	  o Wheel terrain interaction mechanics is categorized into 4 cases based on wheel pressure and terrain pressure (shown in Fig 1.)
	    ▪ Cases a and b have been studied extensively before, so this article focuses more on cases c and d
	  o Assumptions:
	    ▪ Deflected area of a flexible wheel is horizontally flat and normal stress beneath the flat section is evenly distributed
	    ▪ Contact patch of non-deformable sections are circular arcs
	    ▪ Normal stress in the direction of the tire's width is evenly distributed
	• Interaction Model for Flexible and Rigid Wheels
	  o Model calculates:
	    ▪ Static wheel sinkage
	    ▪ Wheel deflection (based on pressure relationship between wheel and terrain)
	    ▪ Stress distribution at contact patches
	    ▪ Wheel forces and torques
	  o Static Sinkage and Wheel Deflection:
	    ▪ For a wheel, the amount of deflection and static sinkage it has generates a vertical reaction force, which balances the wheel load
	    ▪ Vertical reaction force is the sum of force generated at non-deformed section and the force on the flat section
	      • Force on flat section = Wheel pressure due to stiffness x wheel width x length of wheel flat section
	      • Formula for force on non-deformed section is shown in equation 2
	    ▪ Vertical reaction force of a wheel depends on the amount of deflection, wheel static sinkage, and length of the flat section
	  o Normal Stress and Shear Stress Distribution:
	    ▪ Normal stress along the flat section is assumed to be distributed evenly
	    ▪ θf and θr are the entry and exit angles of the wheel contact patch
	    ▪ Wheel slip here is defined as the circumferential velocity of the wheel – longitudinal travelling velocity divided by the circumferential velocity of wheel

	• Assumes that t values range from –1 to 1 ▪ Shear deformation of granular terrain occurs when a wheel drives on it. Shear stress formula is shown in equation 10 ▪ Deformation of the front and rear sections depends on the slip ratio and the contact angle (equation 11) ▪ Hear deformation at the flat section = relative displacement from angle at which the wheel initially deflects o Wheel Force: ▪ Wheel force is the sum of the forces generated on each section of the wheel contact patch ▪ Forces are obtained by integrating normal and shear stresses ▪ Vertical force for the driving wheel is the sum of the vertical forces generated at the front, rear and flat sections ▪ Thrust force of the wheel can be calculated using equation 14 ▪ Resistance due to wheel deflection can be calculated using equation 15 • Equation 16 modifies it to include wheel deflection, which is intended for flexible wheels ▪ Drawbar pull is the difference between the thrust and resistance force o Tractive Efficiency: ▪ Ratio of output power to input power ▪ $\eta = \frac{DP \cdot v_x}{T\omega} = \frac{DP(1-s)r}{T}$ • T is the input torque to the driving axle ▪ In a steady drive, driving torque is equal to the resistance torque ▪ Resistance torque is the sum of the shear stress around the circumference of the wheel • Simulation Study: o Evaluated traction performance of wheels with different internal pressures based on sinkage, drawbar pull, resistance torque and tractive efficiency o 4 different air pressures tested were 1250, 2500, 5000 and 10,000 (rigid wheel) Pa. o Procedure:

	▪ Put wheel load and slip ratio ▪ Find wheel deflection at static states ▪ Calculate wheel sinkage based on equation 13 ▪ Calculate thrust, resistance, and drawbar pull force ▪ Calculate tractive efficiency *These calculations are done at varying slip ratios o **Wheel deflection increases when wheel pressure decreases** o **Wheel sinkage decreases with decreasing wheel pressure** ▪ Because this generates a larger flat section of the wheel, thus resulting in less sinkage o Fig 5. shows us that the wheel's sinkage of the most rigid wheel increases with its slip ratio (because shear deformation of the wheel increases with increasing slip ratio) o Sinkage of wheels with other air pressures is almost constant regardless of slip ratio because the flat section of the wheel supports its vertical load o **Drawbar pull increases with slip ratio regardless of wheel pressure** o Wheel with the lowest pressure generates a relatively small drawbar pull o **Shearing direction of the flat section is parallel to the direction the wheel is travelling, thus increasing the thrust** o Flat section of the flexible wheel helps increase drawbar pull, but also requires an increase of the input torque to the wheel o Tractive efficiency has a maximum curve at 2500 Pa at every slip ratio, meaning this tire pressure has the best traction performance o **Flexible wheels with too low wheel pressure don't perform well on rough terrain.** • Summary: o Traction is determined by drawbar pull and resistance torque ▪ Both of these are small in rigid wheels but large in flexible wheels o Optimal wheel pressure was based on wheel load, terrain stiffness, and wheel structure o Proposed model addresses both flexible and rigid wheels because these results align with past research done on both o In the future, these researchers want to focus on the

<table>
<tr><td></td><td>experimental validation of their model

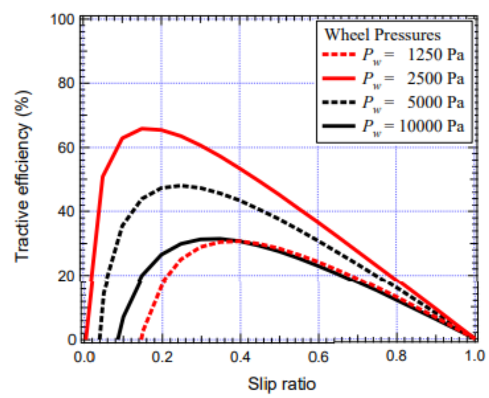
Article Summary:
The article presents a terramechanics-based model that predicts and compares the traction performance of flexible and rigid rover wheels on deformable terrain. By accounting for both wheel structural stiffness and soil stiffness, the model simultaneously calculates wheel sinkage and wheel deflection, dividing the wheel - soil contact into three sections: front, flat, and rear, to compute normal and shear stress distributions. Simulation results for wheels with different internal pressures show how the wheel's flexibility influences drawbar pull, sinkage, resistance torque, and overall tractive efficiency. Notably, the study finds that neither fully rigid nor highly flexible wheels perform best; instead, an optimal intermediate wheel pressure yields the highest traction efficiency on rough terrain.</td></tr>
<tr><td>Research Question/Problem/ Need</td><td>Problem: Current wheel-terrain models can effectively evaluate interaction of rigid wheel and flexible wheels on both granular and solid terrain individually, but there isn't a model that explicitly does both.</td></tr>
<tr><td>Important Figures</td><td>


Fig. 8. Tractive efficiency with varied wheel pressure
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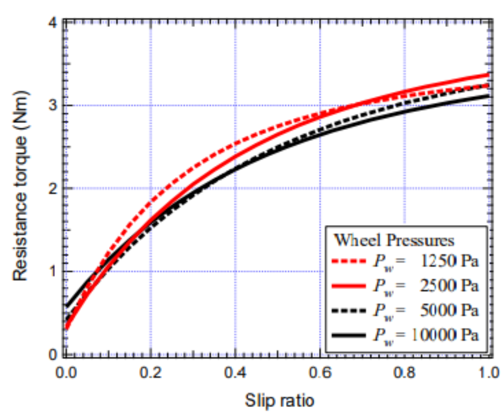

Fig. 7. Resistance torque with varied wheel pressure
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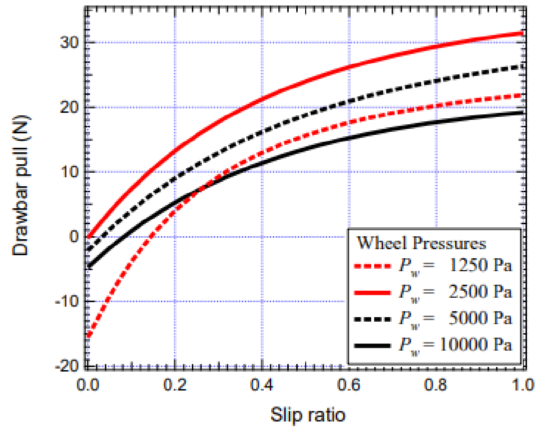

Fig. 6. Drawbar pull with varied wheel pressure

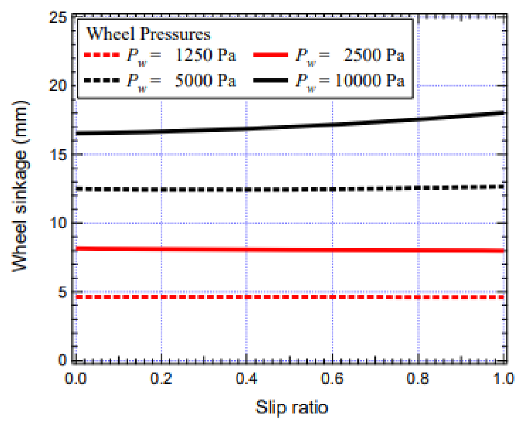

Fig. 5. Wheel sinkage with varied wheel pressure

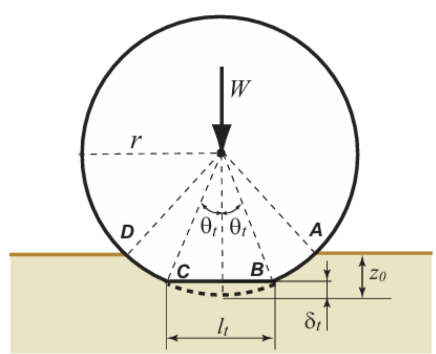

Fig. 2. Wheel-terrain model at static state

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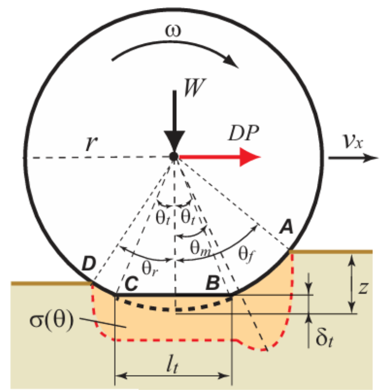
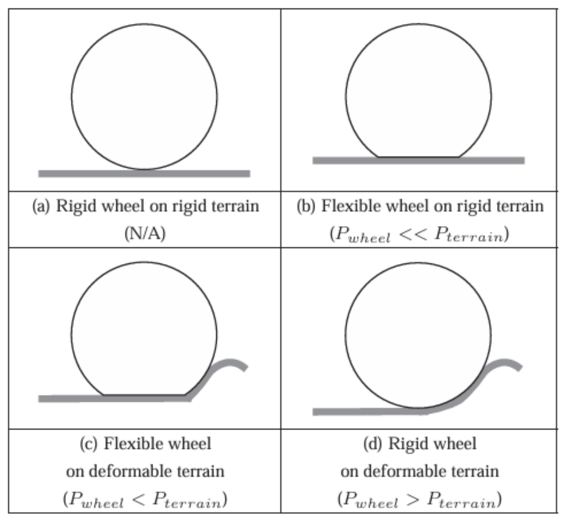


- Fig. 3. Wheel-terrain model: Normal stress distribution of driving wheel



- Fig. 1. Four categories for wheel-terrain interaction
</td></tr>
<tr><td>VOCAB: (w/definition)</td><td>

Normal Stress: normal force that is acting on per unit area on a surface; calculated by dividing the normal force by the cross-sectional area
Static Wheel Sinkage: sinkage based purely on wheel load
Wheel Deflection: deformation of a tire under a certain amount of load
Shear Deformation: the change in shape of an object caused by opposing forces that cause its internal layers to slide past one another
Drawbar Pull: is the horizontal pulling force a vehicle can exert at its drawbar or hitch to pull a load
Tractive Efficiency: efficiency of a wheel in transforming the input power (torque required for wheel driving) to output power at the drawbar (net traction force)

</td></tr>
<tr><td>Cited references to follow up on</td><td>

L. Ding, H. Gao, Z. Deng, K. Nagatani, and K. Yoshida, “Experimental study and analysis on driving wheels’ performance for planetary exploration rovers moving in

</td></tr>
</table>

	deformable soil," J. of Terramechanics, vol. 48, pp. 27-45, 2011. • H. B. Pacejka, Tyre and Vehicle Dynamics, Butterworth-Heinemann, Oxford, 2002 • S. Narita, M. Otsuki, S. Wakabayashi, and S. Nishida, "Terramechanics Evaluation of Low-Pressure Wheel on Deformable Terrain," in Proc. of the 2011 IEEE Int. Conf. on Robotics and Automation, Shanghi, China, (accepted).
Follow up Questions	• What exactly does their definition of rough terrain contain? Is it just sandy terrain, or does it also include rocky terrain? • What is their experimental set-up going to be like if they empirically try to verify their model? • How is the soil's stiffness included in their model?

Article #19 Notes: A Review on Travelling Performance of Planetary Rovers

Source Title	A Review on Travelling Performance of Planetary rovers
Source citation (APA Format)	Kumar, P., & Jayalekshmi, S. (2015). A review on travelling performance of planetary rovers. *Journal of Basic and Applied Engineering Research, 2*(9), 710 - 714. https://krishisanskriti.org/vol_image/07Jul201512072106z%20%20%20Pala%20Gireesh%20Kumar%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20710-714.pdf
Original URL	https://krishisanskriti.org/vol_image/07Jul201512072106z%20%20%20Pala%20Gireesh%20Kumar%20%20%20%20%20%20%20%20%20%20%20%20%20%20%20710-714.pdf
Source type	Journal Article
Keywords	Travelling performance; Rovers; Slip ratio; Drawbar pull; Models
#Tags	Locomotion

Summary of key points + notes (include methodology)	• Parameters such as the weight, diameter and width are used to evaluate the effectiveness of planetary rover wheels
	  ○ Use of grousers in the wheel also plays a role in its performance
	• Travelling performance depends on if the rover is wheeled or uses tracks for locomotion instead
	• Rovers are usually light weight
	• Slip Ratio and Drawbar Pull:
	  ○ Slippage is measured in terms of slip ratio and drawbar pull
	  ○ Formula: $s = \frac{v_d - v}{v_d}$
	  ○ Where Vd = circumferential velocity; v = actual velocity of the wheel
	  ○ Formula #2: $s = \frac{r\omega - v}{r\omega}$
	  ○ Where w = angular velocity of the wheel; r = radius of the wheel; v = actual travelling velocity of the wheel
	  ○ Slip ratio of 0 means a better travelling velocity because no slip is occurring
	  ○ When calculating Drawbar Pull, the slope's angle also needs to be taken into account: $DP = mg \sin\theta$
	  ○ M = mass of vehicle; g = acceleration due to gravity; theta = slope angle

- Vertical Force is $F_z = rb \int_{\theta_1}^{\theta_2} [\tau_s(\theta) \sin\theta + \sigma(\theta)\cos\theta] d\theta$
- Evaluation of Stresses:
  - For wheels on loose soil, the maximum normal stress occurs is the area between its forward and backward portions

    Normal stress in the forward region (i.e. $\boldsymbol{\theta}$ lies between θ_m and θ_1),

    $$\sigma = (k_1 + k_2 b)[\frac{r}{b}(cos\theta - cos\theta_1)] \quad (7)$$

    Normal stress in the forward region

    (i.e. $\boldsymbol{\theta}$ lies between 0 to θ_m is expressed as

    $$\sigma = (k_1 + k_2 b)[\frac{r}{b}\left(\cos[\theta_1 - \frac{\theta}{\theta_m}(\theta_1 - \theta_m)] - cos\theta_1\right)]^n \quad (8)$$
  -
  - Where k1 and k2 = the pressure sinkage constants; b = wheel width; r = radius of wheel; n = soil deformation exponent
  - Normal stress can also be calculated using:

    $$\sigma(\theta) = \sigma_{max}[cos\theta - cos\theta_1]$$

    $$\sigma_{max} = (ck_c + \rho k_\phi b)(\frac{r}{b})^n$$
  - Where c = cohesion; p = bulk density of soil; theta 1 = entry angle; theta 2 = exit angle
  - For wheels on loose soil, maximum shear stress is calculated using a modified version of Mohr's relationship
  - Formula: $\tau_s = (c + \sigma(\theta)\tan\phi)[1 - e^{-j_s(\theta)/k_s}]$
- Effect of Size Parameter on Travelling Performance:
  - Comparison of different parameters used in other research articles
  - Grand et al. (2002), velocity-based algorithm that can improve vehicle traction and considers the vehicle's stability
  - Yoshida et al. (2003), conducted tests on a physical test bed to study wheel-terrain interactions in a slip-based traction control planetary rover
  - Bauer et al. (2005), discovered that an increase in number of grousers causes an increase in the vehicle's drawbar pull, which was very similar to the experimental results
  - Wong et al. (2006) compared the traction of tracks and wheeled vehicles by measuring the shear stress and thrust of the vehicle. The tracked vehicle had more traction of cohesive soil due to its larger surface area
  - Michaud et al (2006), modified a wheel design then measured its traction performance in terms of how well the wheel performed while traversing obstacles and slopes.
  - Lui e al. (2008), analyzed grouser placement and orientation on small rigid wheels and its effects on vehicle performance. Vehicle performance was measured based off of drawbar pull and driving torque
  - Sutoh et al. (2010), verified through simulations and experimentally that increasing a wheel's width would also decrease its slip ratio
  - Ding et al. (2011), studied the effects of vertical load and wheel moving

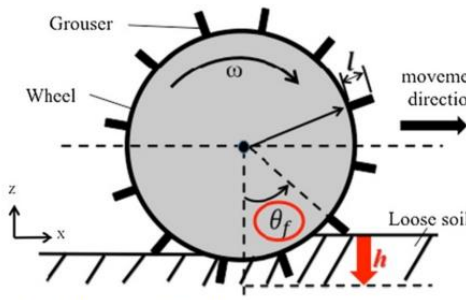
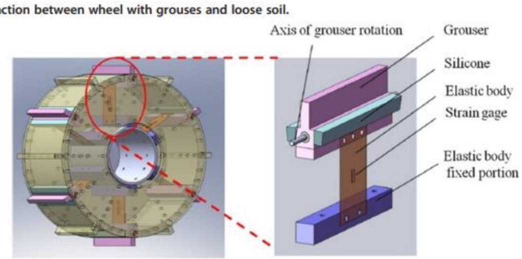
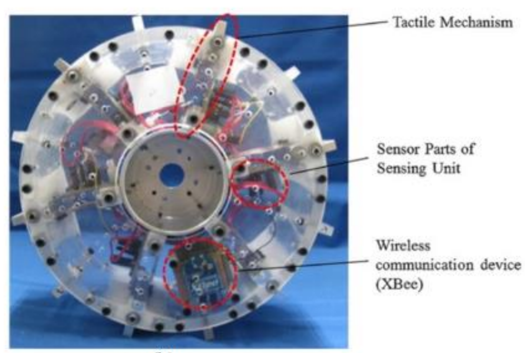
	velocity on the wheel's driving performance while changing diameter, width, grouser number, and grouser height. Found that the grouser height affects the driving performance more than and increase in the wheel's radius o Ishigami et al. (2011), studied flexible vs rigid wheels on deformable terrain and found the optimal wheel pressure based on the wheel's load o Lizuka et al. (2011), measured the slip ratio of a variety of different shaped lugs and found that wheels larger lug lengths and larger radius has better performance o Sutoh M et al. (2011), experimented with different number and heights of grousers o Sutoh et al. (2012), used a linear travelling speed model to determine the number of grousers of a wheel. Found that large number of grousers give better tractive results, but this need to be verified through more experiments o Sutoh M et al. (2012), evaluated the performance of 4 wheeled rovers under different vertical loads, and wheel diameters. A decrease in travelling performance was noticed when the wheel had a higher load on it. o Skonieczny et al. (2012) found an expression to find the optimal spacing between grousers, which he verified through a series of experiments. The equation relies on the wheel and operating parameters to determine the maximum grouser spacing allowed o Ding et al. (2012) studied the slip ratio of wheels with grousers, and verified his results through a simulation o Sreenivasulu (2014) created a lunar soil simulant o Yamamoto et al. (2014), Lok at the soil reaction force s on a single grouser in a variety of mobility situations of rover wheels Article Summary: The article A Review on Travelling Performance of Planetary Rovers examines how planetary rovers move and operate on challenging extraterrestrial terrain. It reviews different rover mobility systems such as wheel design and locomotion strategies, and analyzes how factors like soil properties, slope, and obstacles affect rover performance. The paper also discusses past and current rover designs to highlight common mobility challenges, including slippage, sinkage, and energy efficiency, and emphasizes the importance of optimizing rover design to improve reliability and traversal capability on planetary surfaces.
Research Question /Problem/ Need	To provide an overview of size parameters of rover wheels, such as weight, diameter and width, and effect on a rover's performance.
Important Figures	N/A
VOCAB:	• **Drawbar Pull:** the difference between the soil thrust and external resistance of the

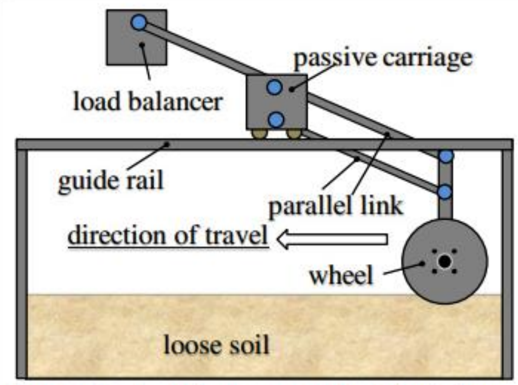
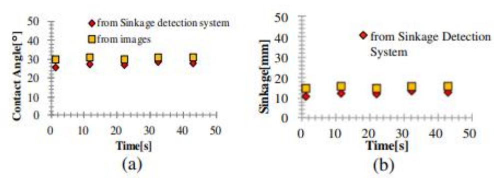
(w/definition)	soil • **Shear Stress:** measure of how much force is applied parallel to a material's surface • **Normal Stress:** internal force perpendicular to the cross-sectional area of a material
Cited references to follow up on	• Wong J.Y. (2001). Theory of ground vehicles, 3rd York: Wiley–Interscience. • Yoshida K, Nagatani K, Miwa and Ishigami G, (2007). "Terramechanics based model for steering Maneuver of planetary exploration rovers on loose soil". Journal of Field Robotics. Vol.24, No.3, 233-250. • Liu J, Gao H. and Deng Z., (2008). "Effect of straight grousers parameters on motion performance of small rigid wheel on loose sand." Information Technology Journal, 7(8):1125-1132.
Follow up Questions	• How were these questions derived? • How are these formulas applied to real-life models • How can the formulas be incorporated in to autonomous rovers?

Article Notes #20: Study on grouser mechanism to directly detect sinkage of wheel during traversing loose soil for lunar exploration rovers

Source Title	ROBOMECH Journal
Source citation (APA Format)	Iizuka, K., Sasaki, T., Suzuki, S., Kawamura, T., & Kubota, T. (2014). Study on grouser mechanism to directly detect sinkage of wheel during traversing loose soil for lunar exploration rovers. *ROBOMECH Journal*, *1*(1), Article 15. https://doi.org/10.1186/s40648-014-0015-6
Original URL	https://link.springer.com/article/10.1186/s40648-014-0015-6
Source type	Scientific Journal
Keywords	Sinkage; Grousers; Wheel; Loose Soil; Lunar Rovers
#Tags	Locomotion

Summary of key points + notes (include methodology)	• Traditional planetary rover wheels have to deal with slippage and sinkage
	• This mechanism uses the wheel's contact geometry to predict sinkage
	• Uses terramechanics models to describe wheel-soil interactions
	• Looked at prior research on flexible wheels etc.
	• However no mechanism exists thar directly detects sinkage
	• Author proposes a grouser mechanism with inbuilt sensors as a solution
	• Methodology:
	    ○ Created a single wheel test bed to simulate the mechanism with separate loads and test the wheel on different inclinations
	    ○ Experiments performed of loos soil simulant
	    ○ Strain gauges gathered data during each of the tests
	• Results:
	    ○ Generates graphs for the contact angle and sinkage of the wheel
	    ○ Increasing load, causes increases sinkage, which also corresponds to change in the wheel's angle
	    ○ Strain data collect through sensors is verified through visual image processing
	Article Summary:
	This article looks at a grouser-based sensing mechanism designed to directly detect wheel sinkage in loose soil for lunar exploration rovers.

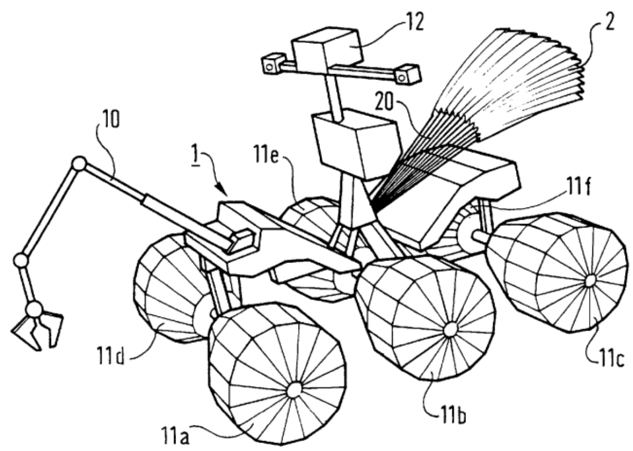
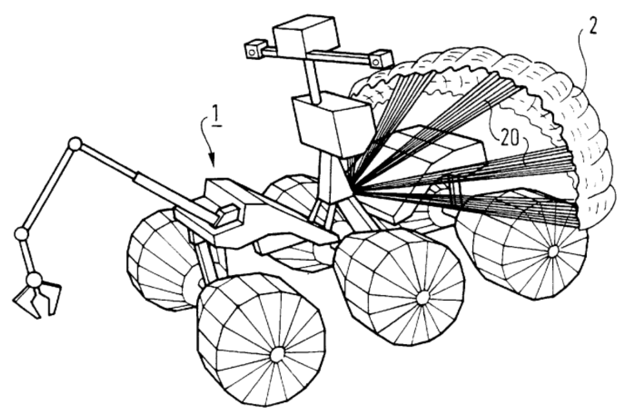
	The authors propose integrating elastic grousers equipped with strain gauges into a rover wheel so that changes in contact force and angle during soil interaction can be measured in real time. Through single-wheel experiments on loose soil simulant, they demonstrate that the sensor data closely correlates with visually measured sinkage, validating the mechanism's accuracy. The study concludes that this approach enables direct, real-time detection of wheel sinkage, which could help future planetary rovers assess terrain traversability more effectively and avoid becoming immobilized in hazardous terrain.
Research Question/Problem/ Need	How can a wheel mechanism be designed to detect the sinkage of a lunar rover while the vehicle is traversing on loose soil?
Important Figures	 - **Figure 1** Interaction between wheel with grouses and loose soil.  - **Figure 3** Proposed wheel with grouser mechanism which can acquire concrete information from the loose soil.  (b) -

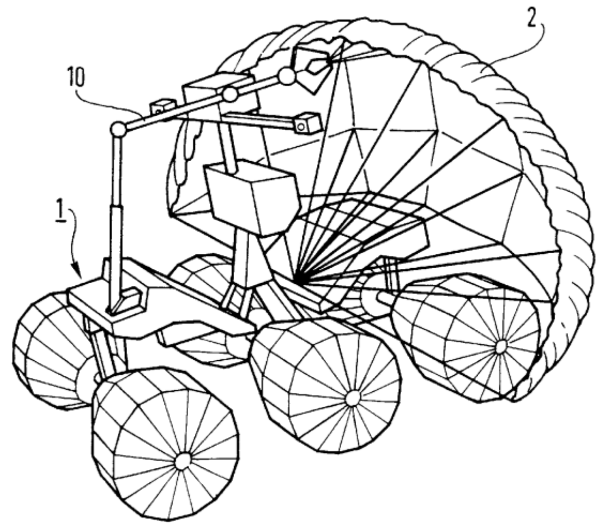
	 **Figure 11** Experimental systems to traverse single wheel on loose soil. -  - **Figure 13** Contacting angle and sinakge (5 kg). **(a)** Contacting angle. **(b)** Sinkage.
VOCAB: (w/definition)	• **Strain:** is the measure of how much a material deforms relative to its original size when a force is applied**.**
Cited references to follow up on	• Senatore C, Wulfmeier M, Jayakumar P, Maclennan J, Iagnemma K (2012) Investigation of Stress and Failure in Granular Soils for Lightweight Robotic Vehicle Applications. The Michigan Chapter of the National Defense Industrial Assocoation (NDIA), Proceedings of the Ground Vehicle Systems Engineering and Technology Symposium, MSTV session (1:30–2:00, THURSDAY, AUGUST 16) • Ding L, Nagatani K, Sato K, Mora A, Yoshida K, Gao H, Deng Z (2010) Terramechanics Based High-Fidelity Dynamics Simulation for Wheeled Mobile Robot on Deformable Rough Terrain. Proc. of the 2010 international conference on Robot and Automation, pp 4922–4927
Follow up Questions	• How can the sinkage detection mechanism be integrated with current autonomous rover path planning methods? • Can this mechanism be modified to detect slippage as well? • How would the performance of this mechanism differ when the rover is driven on other kinds of terrain, such as the Martian terrain?

Article #21 Notes: Method of Protecting a Planetary Rover Vehicle

Source Title	Method of Protecting a Planetary Rover Vehicle
Source citation (APA Format)	Hayard, M., & Anne, J. -C. (1999). *Method of protecting a planetary trover vehicle* (U.S. Patent No. 5,897,156). U.S. Patent and Trademark Office. https://patentimages.storage.googleapis.com/ad/b4/40/10c3dd1ab469ea/US5897156.pdf
Original URL	https://patentimages.storage.googleapis.com/ad/b4/40/10c3dd1ab469ea/US5897156.pdf
Source type	U.S. Patent
Keywords	Autonomous; Shelter; Planetary Rover; Hostile Environment
#Tags	Locomotion

Summary of key points + notes (include methodology)	• Planetary rovers operate in extreme environments
	  ○ Conditions such as harsh temperature, vacuum, no air etc.
	• Electronics and batteries are at risk of damage
	• On moon, the night lasts 14 days, while mars has a lot of dust storms
	• Heaters powered by rover battery is ineffective because it requires insulative materials
	• Their invention would first detect if the environment were about to become hostile, then allow the rover to shelter autonomously
	• Onboard systems are placed on stand-by, and the system might deploy solar panels to gain extra energy
	• The rover would detect a second event that signals safe conditions, telling it when to re-emerge
	• "First event" is what rover uses to initiate protection mechanism
	  ○ Based on if temperature falls below a predetermined threshold or if it's given a direct command
	• "Second event" triggers the rover to emerge
	  ○ Based on temperature rise over threshold or rover radio command
	• Cover is designed to be shaped like a parachute
	• Made of Mylar or similar insulating material
	• Parachute is attached to rover with the use of telescopic rods
	• Telescopic rods extend outward from a central point to have the cover spread around the rover
	• A manipulator arm can be used to assist in this process
	• Robot could also travel to a pre-built shelter, rather than deploying one itself
	• After taking shelter, rover conserves energy by putting all systems on standby and deploying solar panels to gain more energy

	• Main advantages: ○ Reduces the need for batteries ○ Increases misson lifetime ○ Applicable to both Martian and lunar missions ○ Adaptable for a wide variety of environments
Research Question/Problem/ Need	Need: No method exists to allow rovers to detect hostile conditions and act accordingly.
Important Figures	FIG. 1A  - FIG. 1B  -


2
10
1

-

FIG. 1D

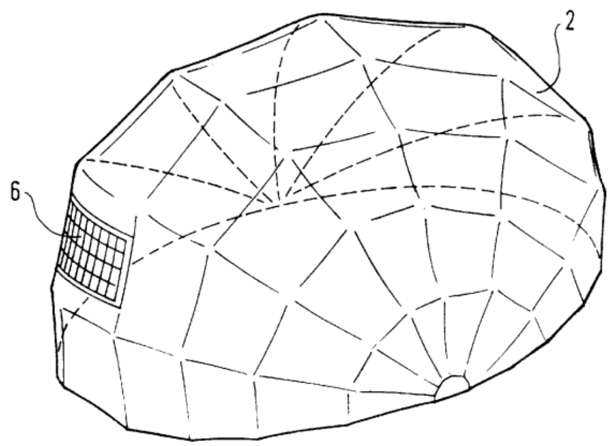

2
6

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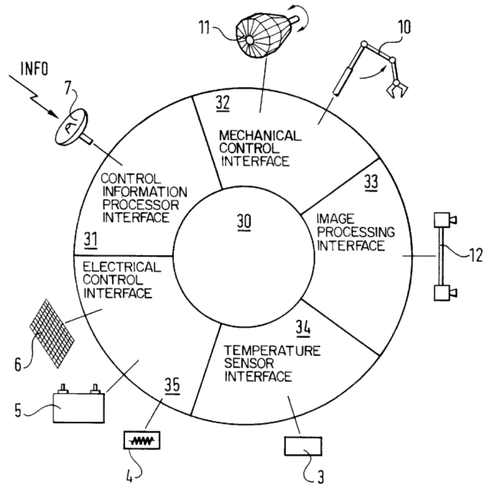
FIG. 4


11
10
INFO
7
32
MECHANICAL CONTROL INTERFACE
CONTROL INFORMATION PROCESSOR INTERFACE
33
30
IMAGE PROCESSING INTERFACE
31
12
ELECTRICAL CONTROL INTERFACE
34
TEMPERATURE SENSOR INTERFACE
6
35
5
4
3

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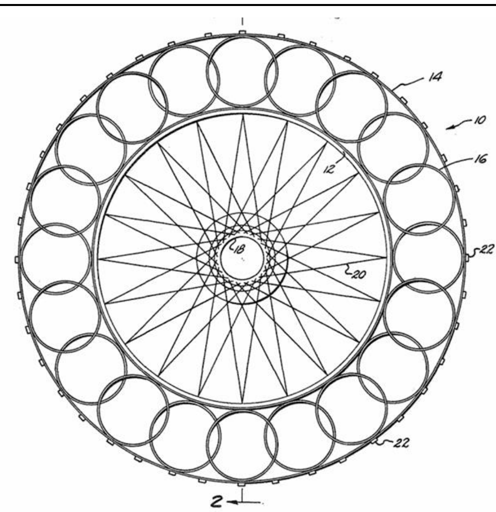
VOCAB: (w/definition)	• **Conical:** cone-shaped
Cited references to follow up on	• N/A
Follow up Questions	• How does this compare to prior similar patents? • What are some engineering trade-offs of this solution • Can shelter methods prevent frost as well?

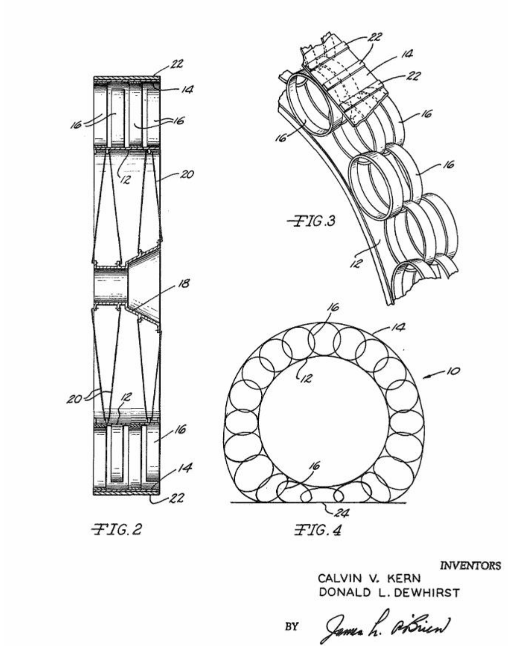
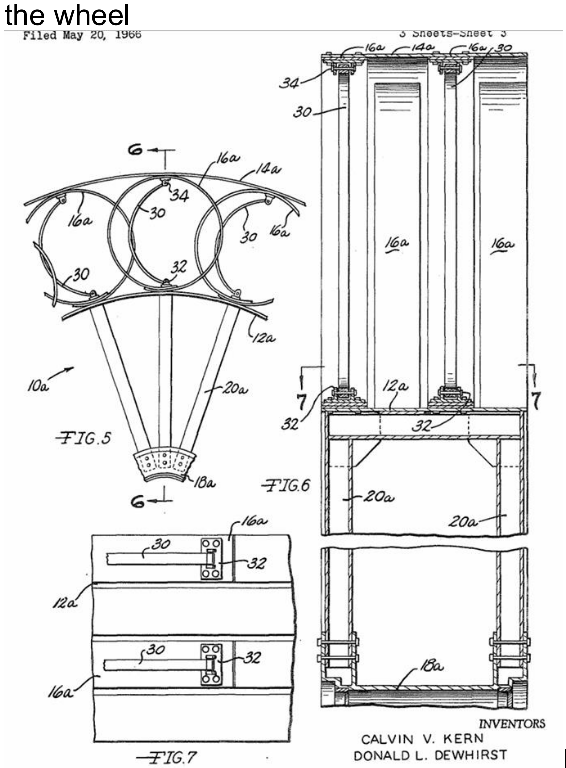
Article #22 Notes: Deformable Vehicle Wheel

Source Title	Deformable Vehicle Wheel
Source citation (APA Format)	Dewhirst, D. L., & Kern, C. V. (1970). *Deformable vehicle wheel* (U.S. Patent No. 3,493,027). U.S. Patent and Trademark Office. https://ntrs.nasa.gov/api/citations/19710009136/downloads/19710009136.pdf
Original URL	https://ntrs.nasa.gov/api/citations/19710009136/downloads/19710009136.pdf
Source type	U.S. Patent
Keywords	Deformable Wheel; Vehicle Wheel; Load Distribution
#Tags	Locomotion

Summary of key points + notes (include methodology)	• Designs a deformable wheel for lunar surface traversal by building the wheel out of circular rings that can deform but then return to their original shape
	• Addresses the need for deformable wheels that can withstand the intense conditions of space and radiation of the moon
	• Wheel needs to avoid cold welding in joints
	  ○ Solved by having a single wheel hub that can be sealed and put under pressure to avoid cold welding
	• Vehicle needs to provide shock absorption and ability to adapt its tread area according to the terrain
	• The outer rim is supported by the flexible rings that are arranged in a circular pattern on the inside of the wheel
	• Inner rim is flexible and made to act like a membrane
	• Outer rim made of titanium because of its flexibility
	• Rings within the wheel frame are resilient enough in the radial direction of the wheel
	• When the wheel is not under a load the inner rings help the wheel retain its shape
	• Inner rings made up of 0.06-inch titanium
	• Treads attached to the outer side of the outer ring (the part that contacts the ground) to increase traction
	• Annular rings are positioned in between the inner and outer rings
	• Inner ring functions to support the ring structures in the center
	• Wheel design also includes retention straps that secure the inner rim' s end to the inner rim
	  ○ This also helps prevent the wheel from excessively deforming
	• Outer rim is also mounted onto a resilient ring that is connected to a hub
	• Flexible out rim and ring members cooperate to ensure the wheel can deform in the radial direction and improve the wheel's shock absorbing and traction capabilities

	• Similar behavior to pneumatic tires
	• Wheel also has the ability to resist thrust in the lateral direction allowing it to better traverse hills and navigate corners
	• Wheel is usable in a variety of temperatures because of the materials being used to make it
	• They claim:
	    o The ring members prevent the rim from slipping, allowing it to resist axial deformation. This increases grip and support when the outer rim is pushed inwards
	    o A 2nd flexible rim is placed inside the first rim, along with rigid supports for additional support
	    o The wheel uses rings instead of adhesives, making the wheel suitable for harsher environments

Research Question/Problem/ Need	Need: Deformable wheels perform better on granular terrain, so there is a need for a deformable wheel design that can withstand the harsh conditions of space for planetary rovers.
Important Figures	 FIG.1 - Front view of wheel

	 - Traversal sectional view of the wheel  - Fig 6: Enlarged cross-sectional view of traversal section of the wheel
VOCAB: (w/definition)	• **Cold Welding:** when two solid metallic pieces join without the use of heat, relying on high pressures to bond • **Annular:** any ring-shaped object
Cited references to follow up on	• N/A

Follow up Questions	• What kind of metal was used to construct the outer circle of the wheel? • What material are the spokes made from? • How was this wheel manufactured?