# Auxiliary Inflatable Wheels for Lunar Rovers: The AIRWHEEL Project

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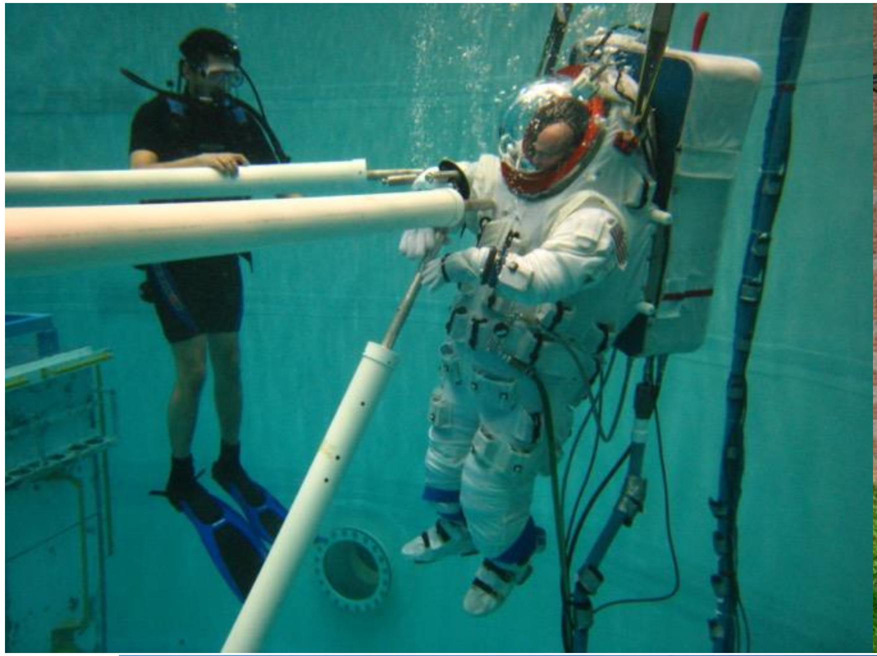
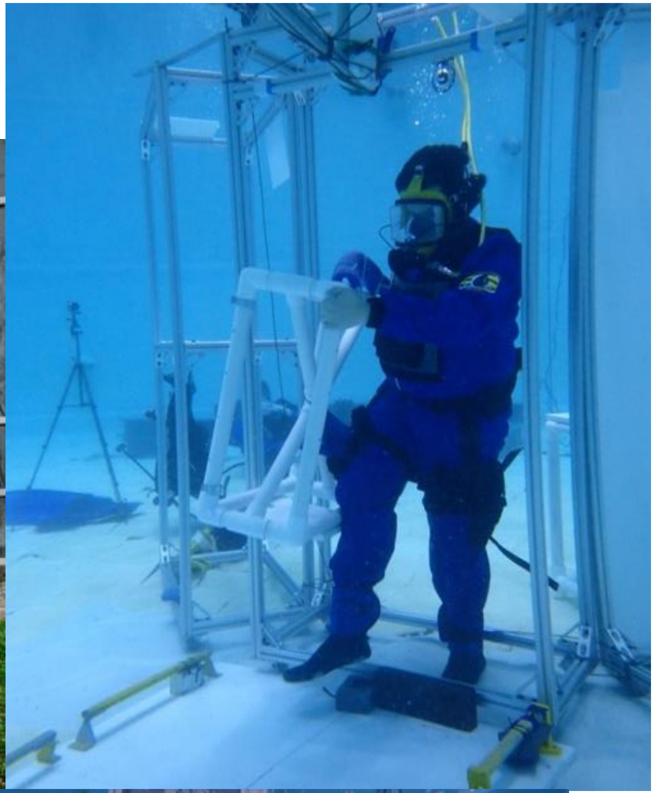
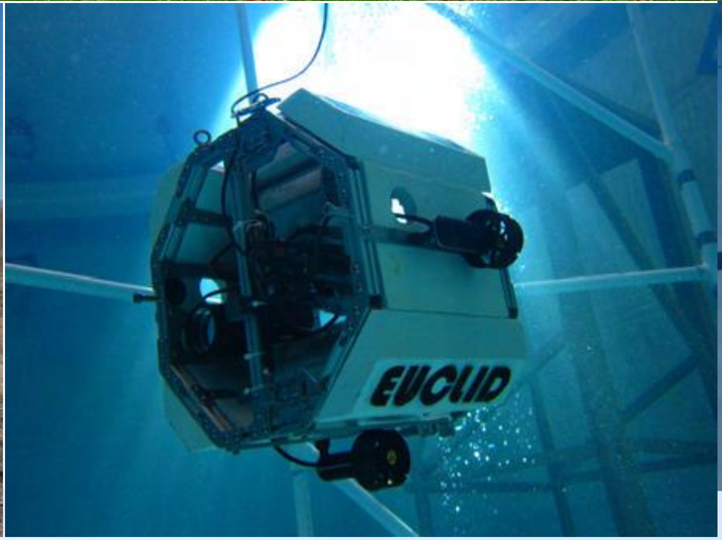
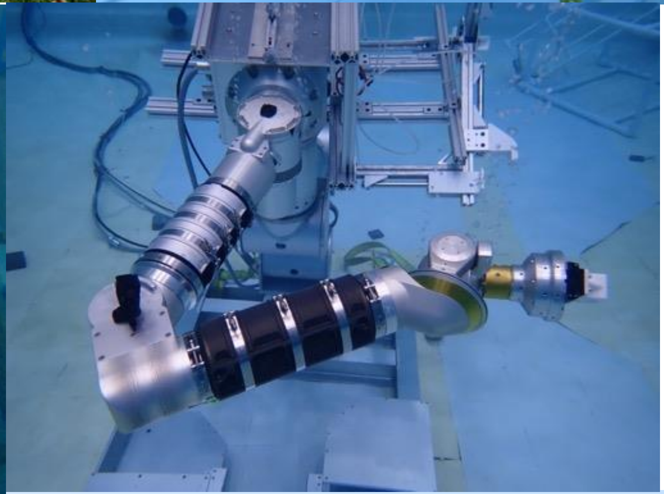
# The Space Systems Lab



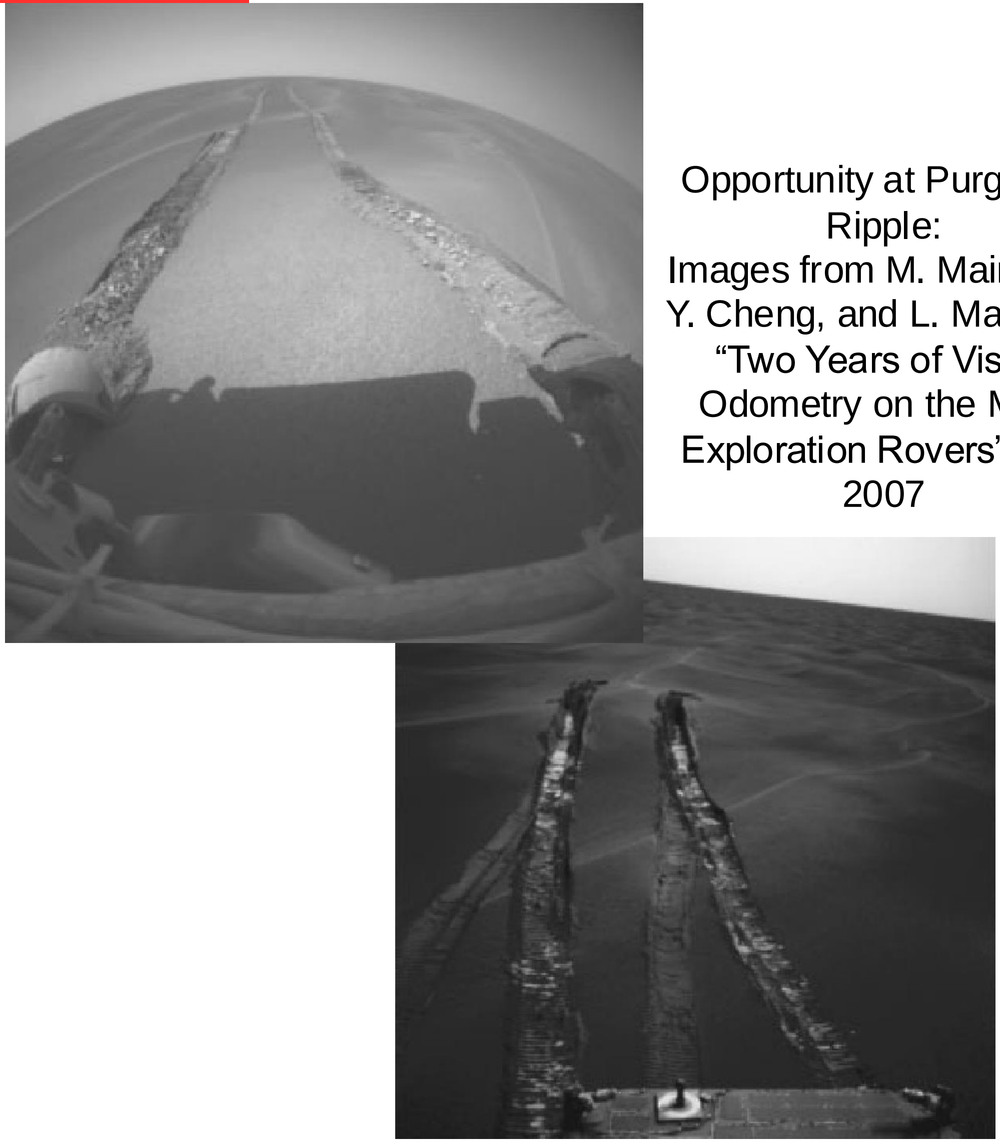




# Rover Exploration Challenges

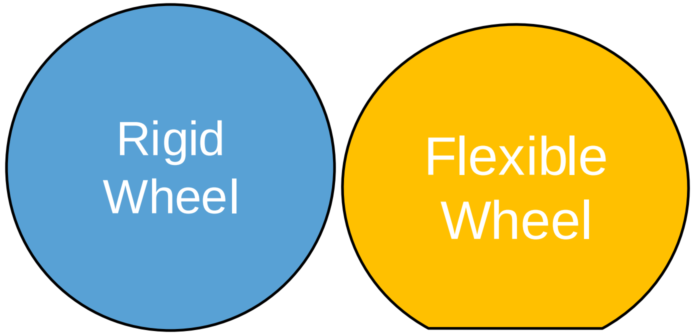
- What role can inflatables play in lunar and Martian exploration?
- The problem
  - Spirit died due to sand trap after 8 months of extrication attempts
  - Opportunity stuck in several sand traps, once stuck over 5 weeks
  - Lunar regolith is less cohesive than Martian, lower gravity lowers traction gain from weight
  - Software and sensors can detect high slip areas *only once trapped inside*
- Can a hardware solution grant more traverse freedom & act as a failsafe?

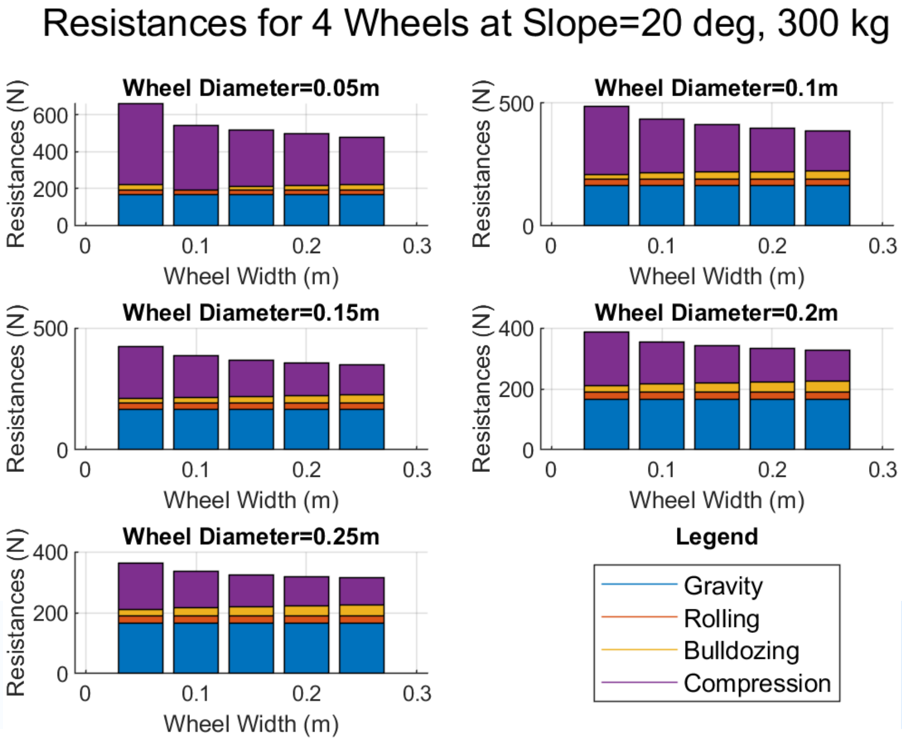


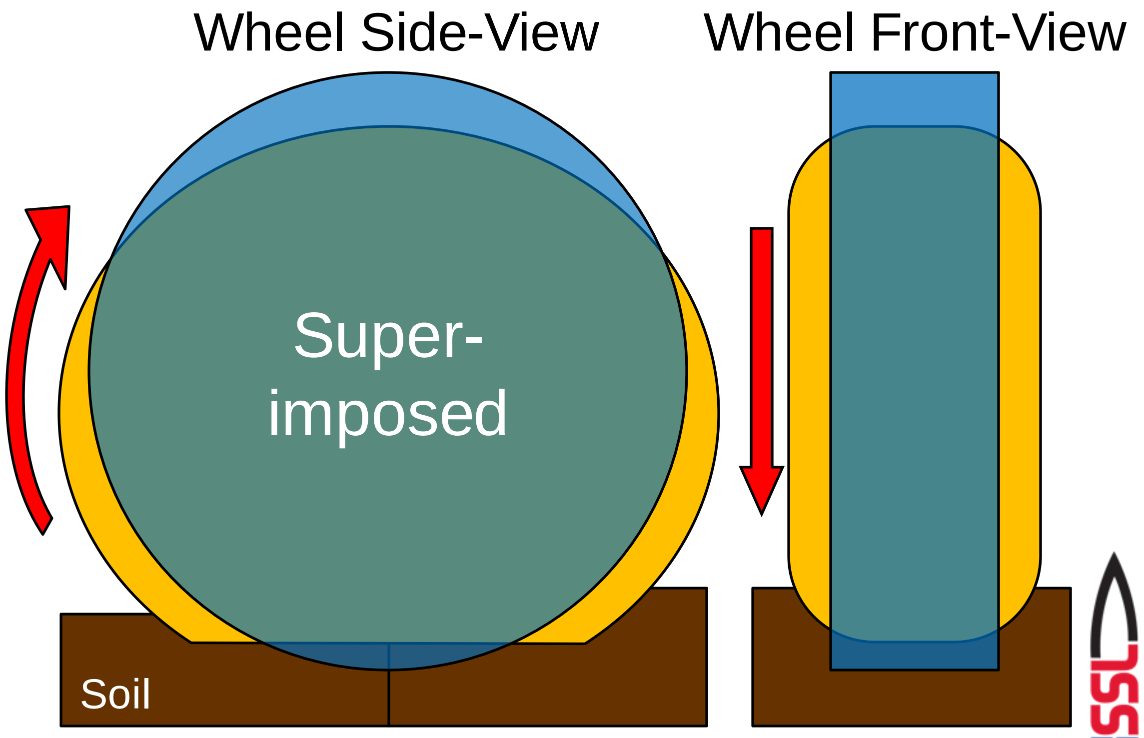
Opportunity at Purgatory Ripple:
Images from M. Maimone, Y. Cheng, and L. Matthies, "Two Years of Visual Odometry on the Mars Exploration Rovers" *JFR* 2007

# Flexible vs. Rigid Wheels

- Flexible wheel
  - Larger contact patch
  - Less ground-pressure (sinkage)
  - Some torque loss
- Rigid wheel
  - Wear-resistant
  - Puncture-resistant

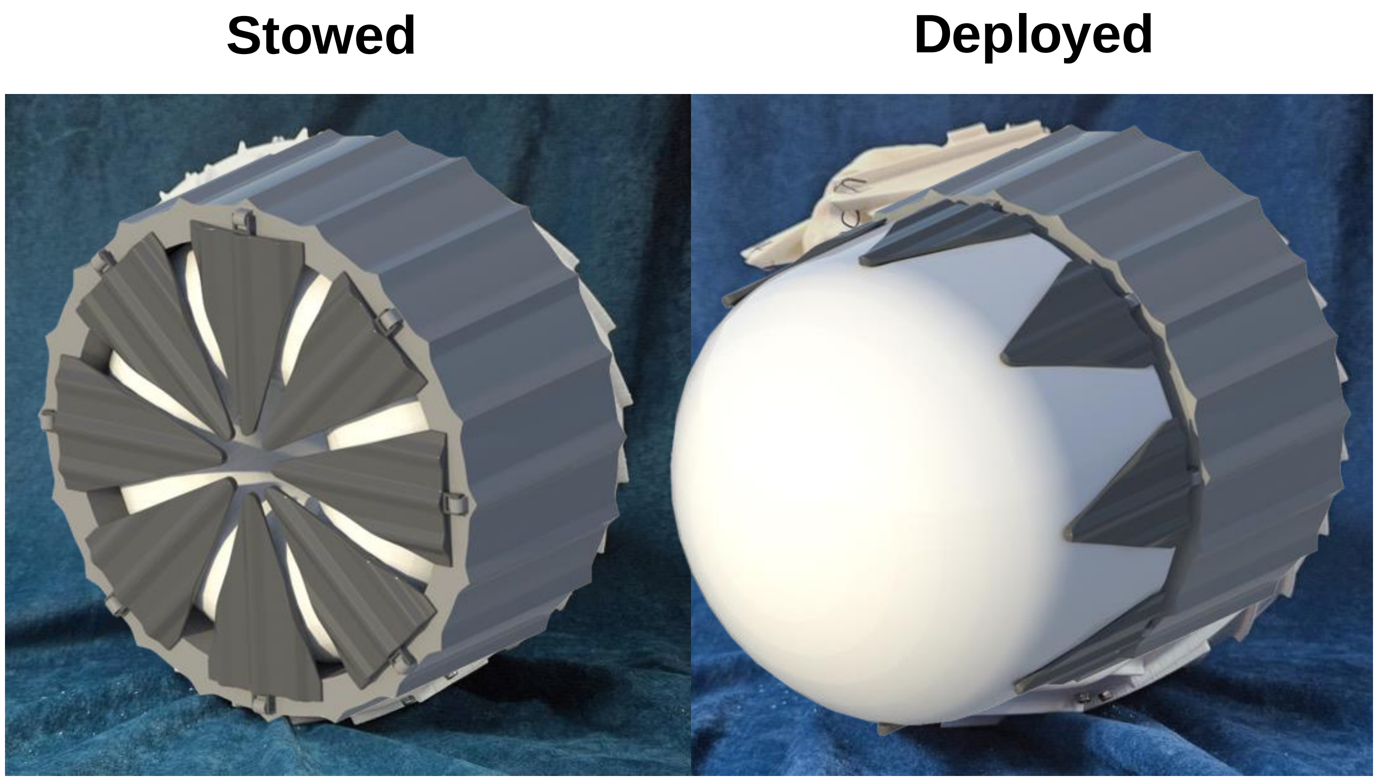


# Overall Concept

- Can we combine the benefits of both?
  - Nominal driving on rigid wheel
  - Loose terrain traverse/extraction with deployed inflatable
  - Hinged grousers assist with torque delivery to ground
- Multi-deployment
  - Internal springs for retraction
  - Potential for gas scavenging

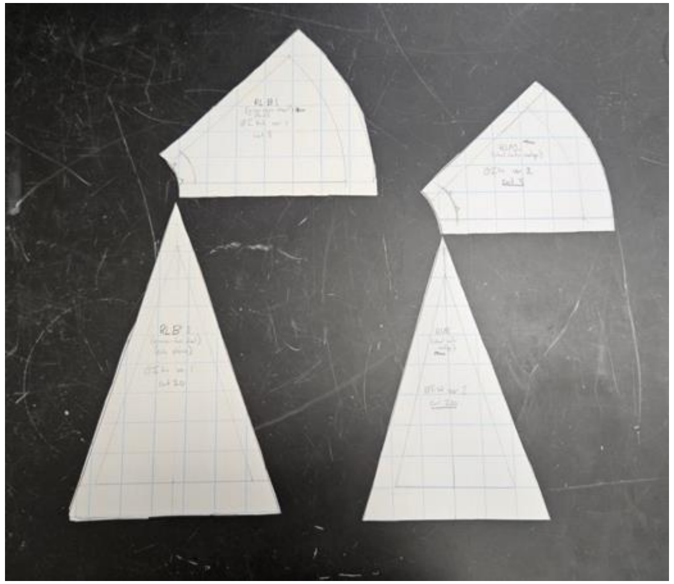


# Inflatable Design

- Pressure bladder
  - Polyurethane coated nylon
  - Toroidal shape first design
  - Developed into a final tube shape
- Restraint Layer
  - 500 Denier Cordura
  - 1000 Denier Cordura used for the grouser-less wheel
  - Triangular front panels and simple side panel

# Softgoods manufacturing

- Pressure bladder
  - Heat sealed by hand
  - Secured to the inner front face of restraint layer to limit twist during use and mounting
- Restraint Layer
  - Machine sewn
  - Front face supports the spring retraction method and the shape of the inflated wheel
  - Aluminum eyelets used at all mounting locations





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# Mechanical Design

- VIPER class wheel
  - 28cm diameter x 4cm width
- Protect soft goods in stowed and deployed configurations
- 5.06 Liters of Storage
  - Softgoods (Pressure Bladder and Restraint Layer)
  - Electronics
  - Inflation/Retraction mechanisms



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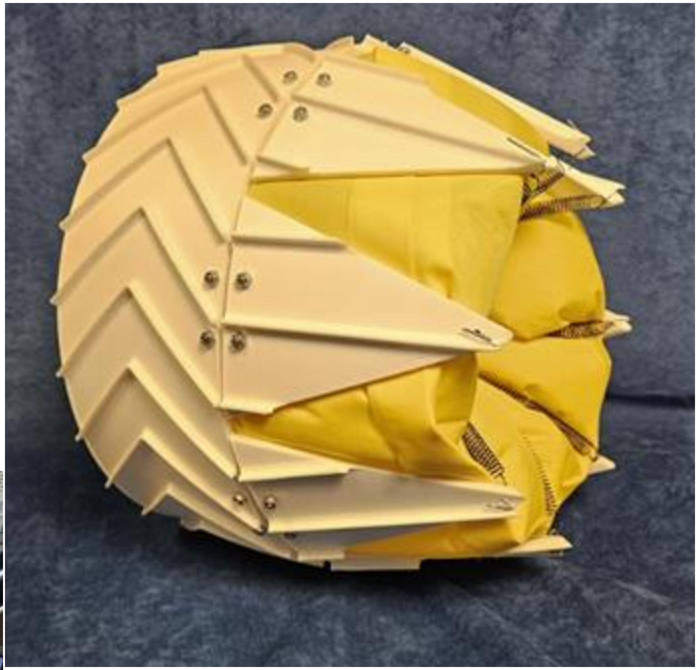
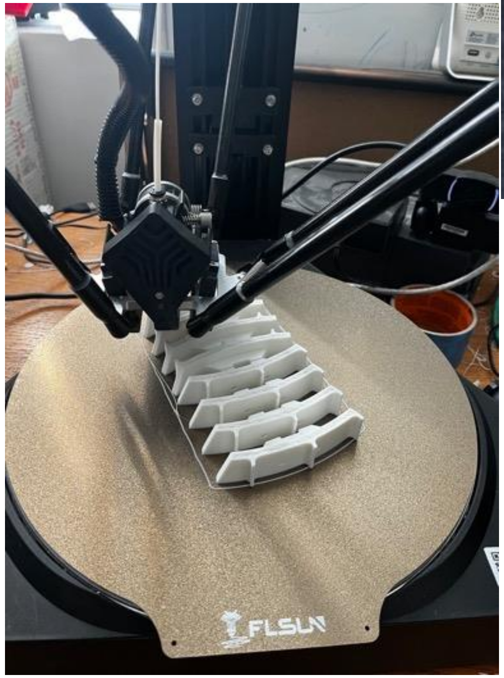
# Wheel Manufacturing

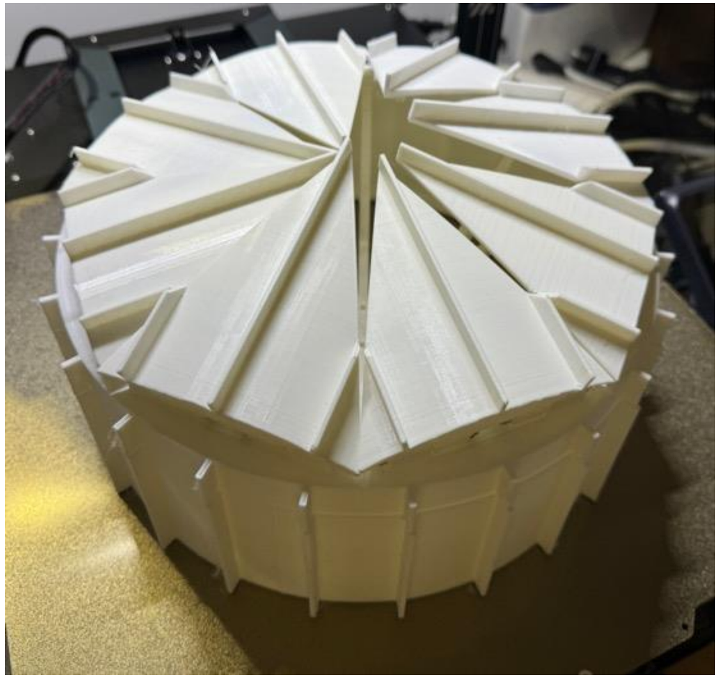
- Rigid
  - Rigid wheel and petals are 3D printed
  - Base and grousers printed separately and mounted via spring hinges
  - Heat set inserts added to retraction cylinder
- Softgoods integration
  - Restraint layer is bolted to the back face of wheel
  - Retraction springs hold in place during inflation and while stowed





# Design Evolution

Early wheel design using existing wheel, retrofitted with deployable grousers and inflatable.

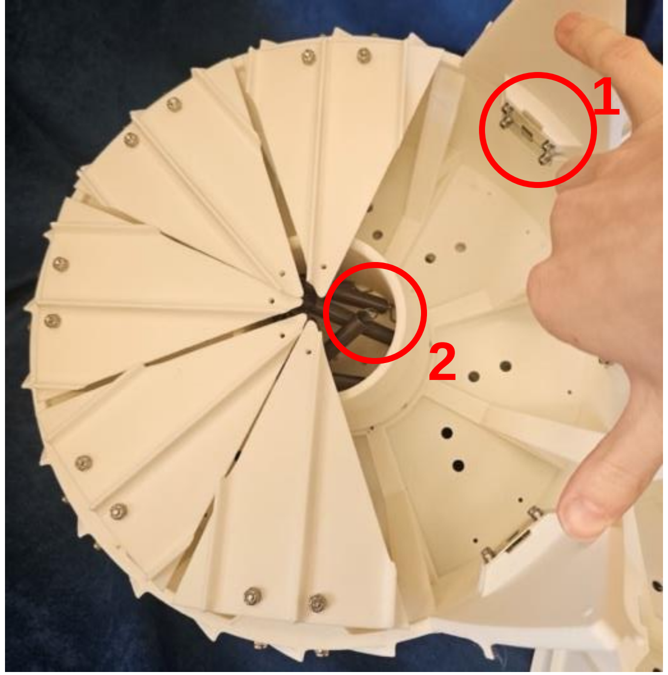


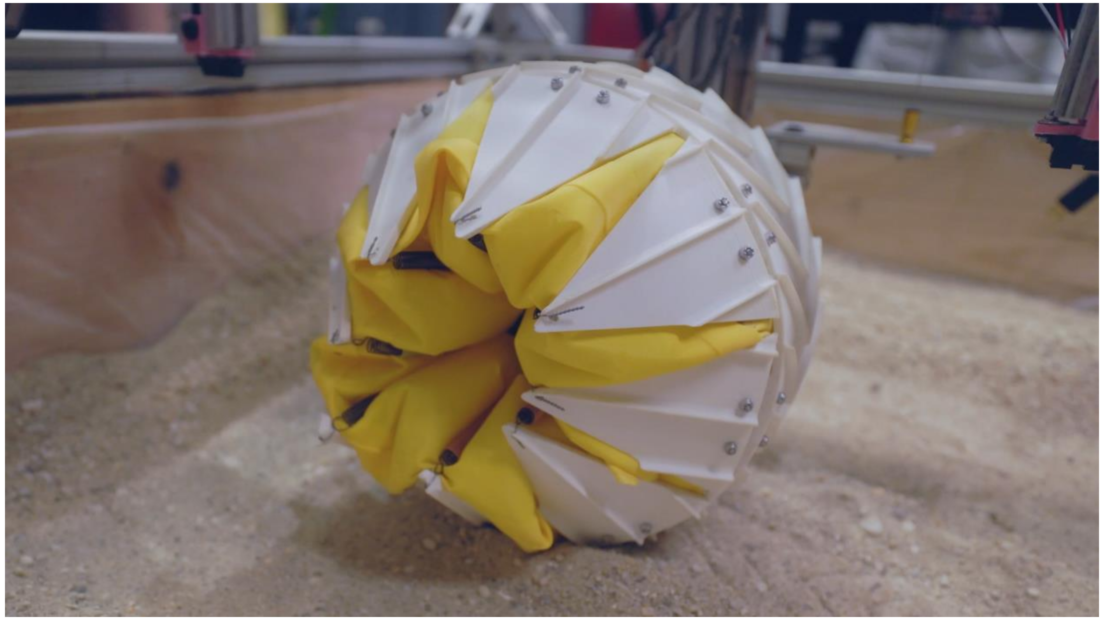
Wheel design with interlocking grousers providing increased protection to inflatable.

Independent triangular petals protect inflatable in stowed configuration and allow inflatable to conform to soil.

# Retraction Method

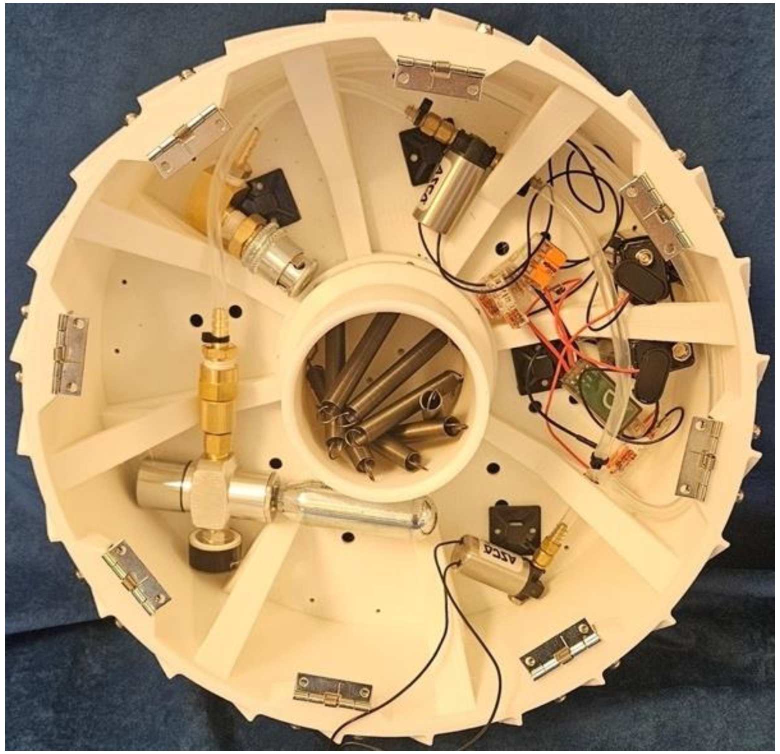
- Vacuum cannot be used to retract inflatable on the Moon!
- A pair of springs per deployable grouser are used for retraction
  - Spring-loaded grouser and tip-mounted extension spring force the inflatable back into stowed configuration
  - Extension spring placement introduces buckles into pressure bladder, allowing it to more easily conform to the wheel shape



# Self-Contained Inflation System

- $CO_2$ was selected as the inflation gas for the earth test unit
  - $CO_2$ liquifies at storage pressures of ~800 PSI, greatly reducing gas canister size
- Inflation system consisted of $CO_2$ pressure regulator, two gas solenoids and two wireless receivers
  - Each gas solenoid + wireless receiver combo controlled either inflation or deflation
- Spent gas was vented overboard

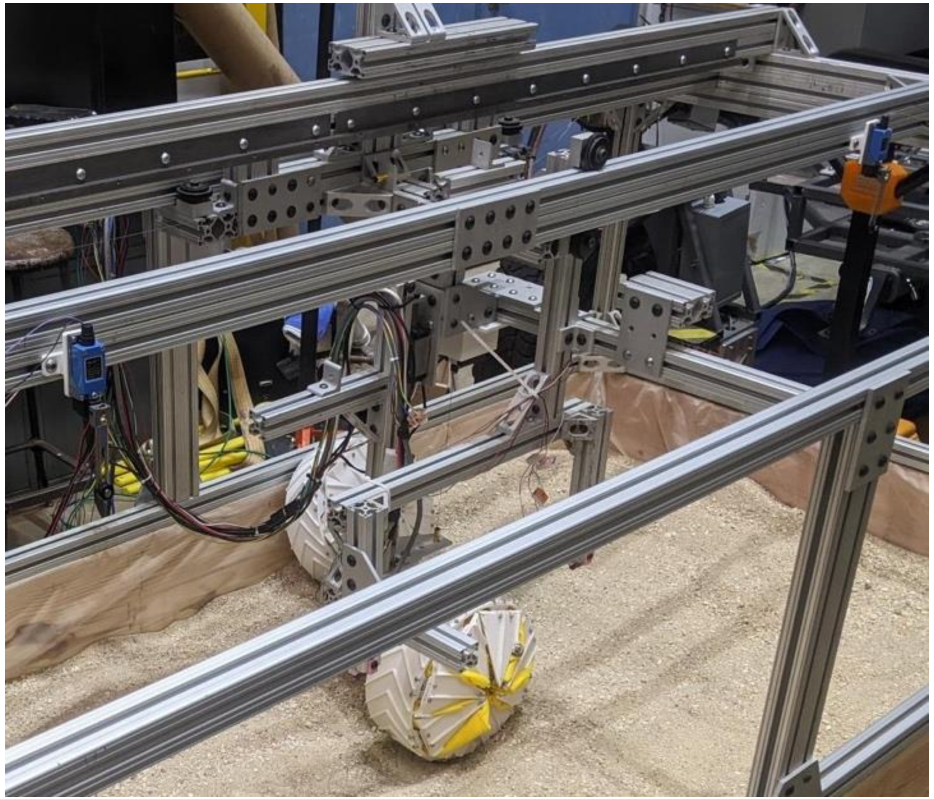


# Wheel Test Rig

- Wheels need to tested in a controlled way
- A wheel test rig captures the wheel forces, position, and velocity while constraining it to move in a straight line
- A powered horizontal stage allows for simulation of variable driving conditions

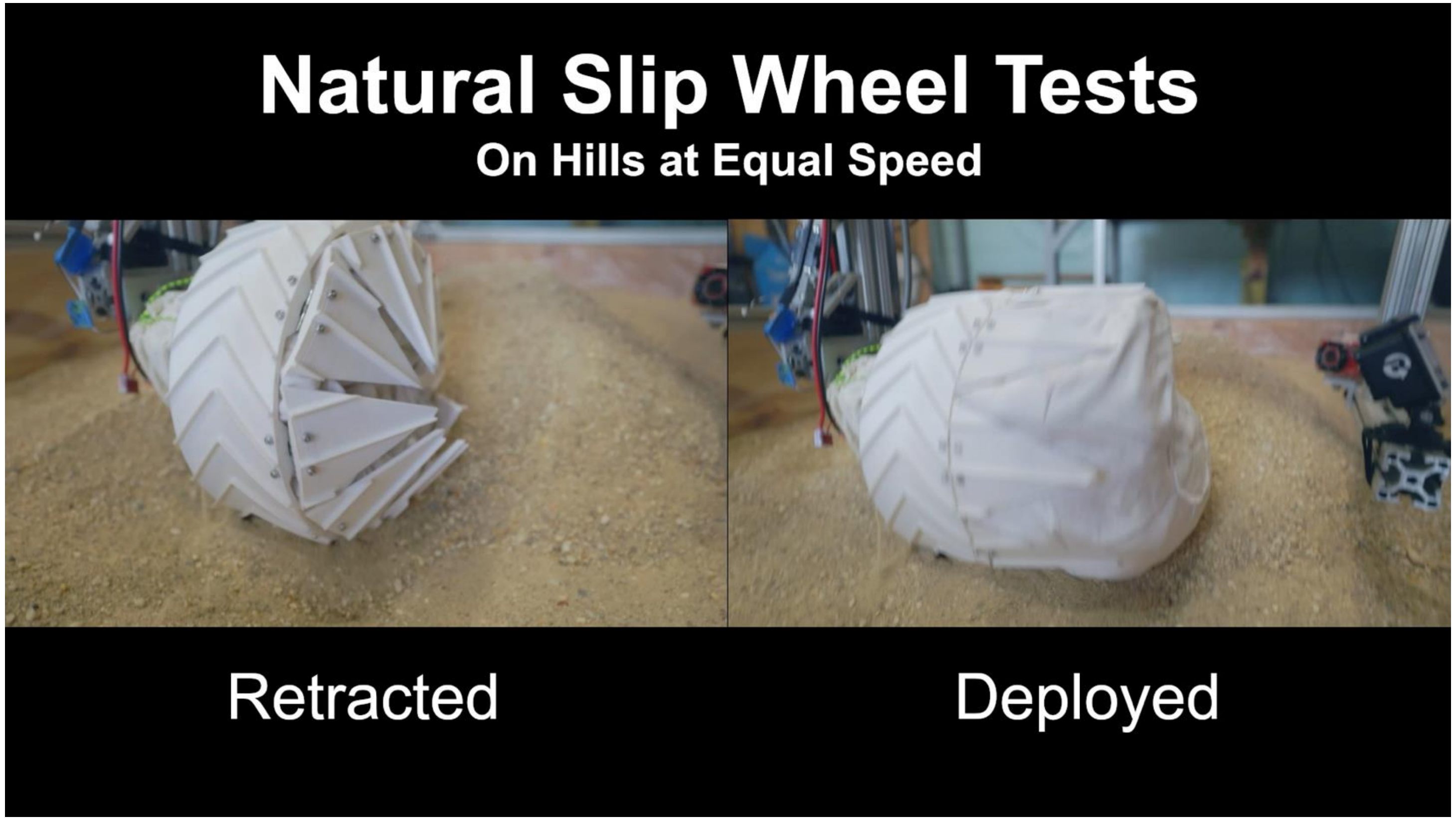
# Wheel Test Rig Evolution

- Wheel test rig is very sensitive to friction and off-axis loading
- Multiple design revisions were needed to get good performance from the horizontal stage



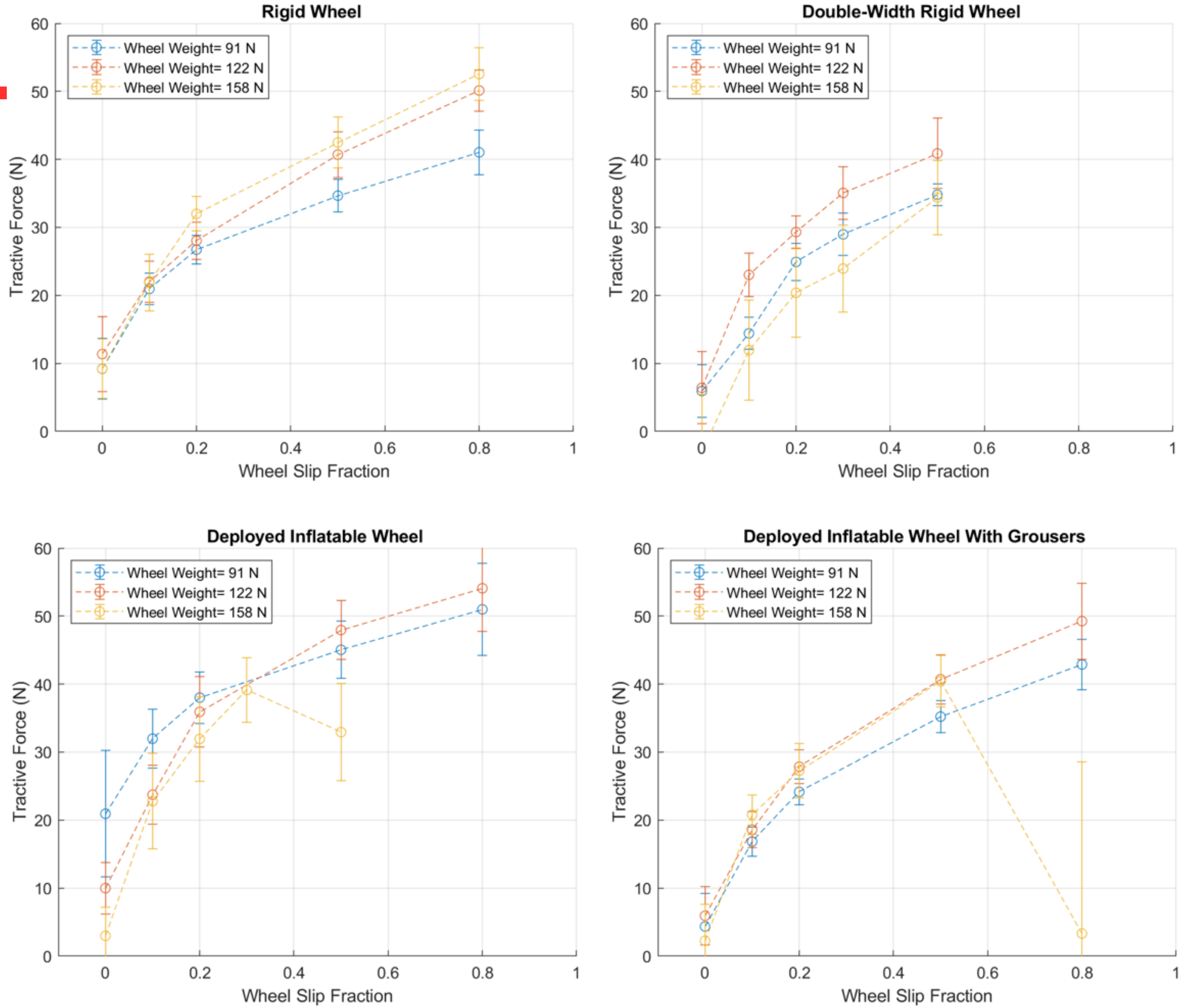
# Wheel Test Rig Deployable Comparison

- Accepts variable diameter and width wheels for direct comparison
- Motor speed, current
- Position along test rig length
- Vertical wheel position
- Soil height before & after
- Force & torque at wheel



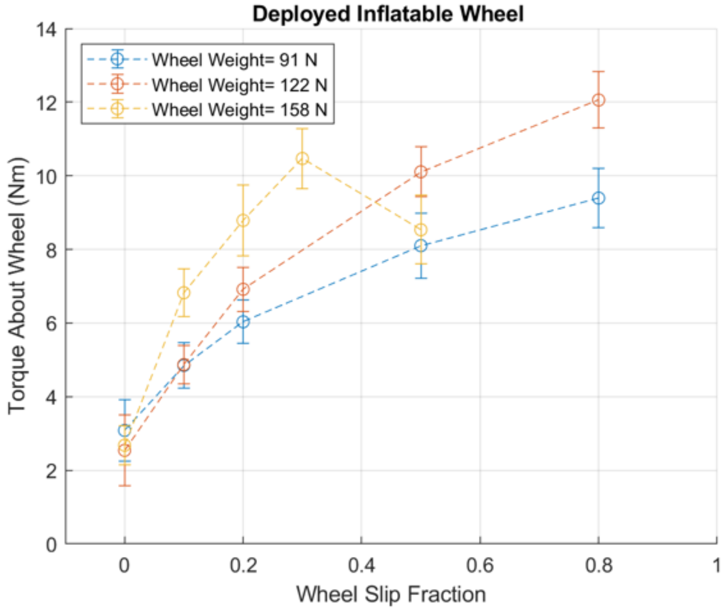
# Testing Data

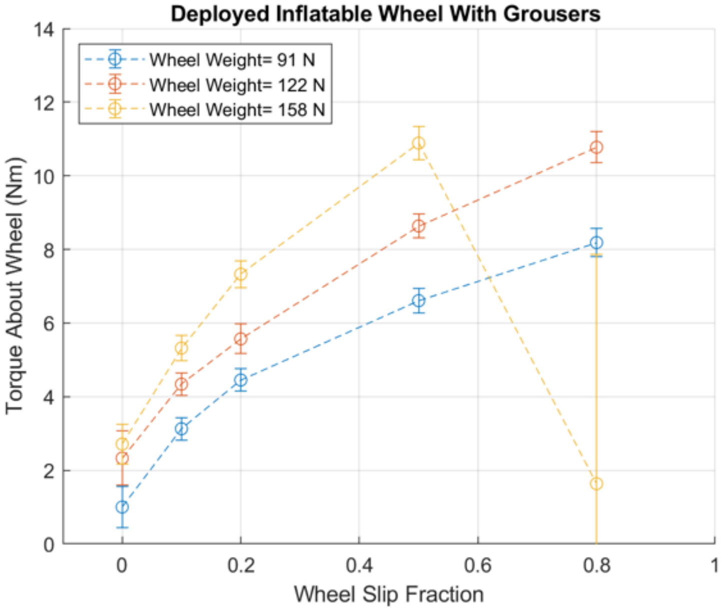
- Inflatables superior to equal-width rigid wheel
- Rigid wheel superior at equal slips
- Inflatable w/o grouser performs best because of larger diameter
- As expected, nominal performance goes to classic rigid wheel



# Grouser Improved Torque Transfer

- No grousers = huge variability in performance
- Grouser petals lower required torque significantly (~25%)
- Both designs reduce ground pressure
  - Reduced slippage in equal conditions
  - Video on next slide!



# Stuck-to-Extraction Test

# 4-Wheeled Rover Test

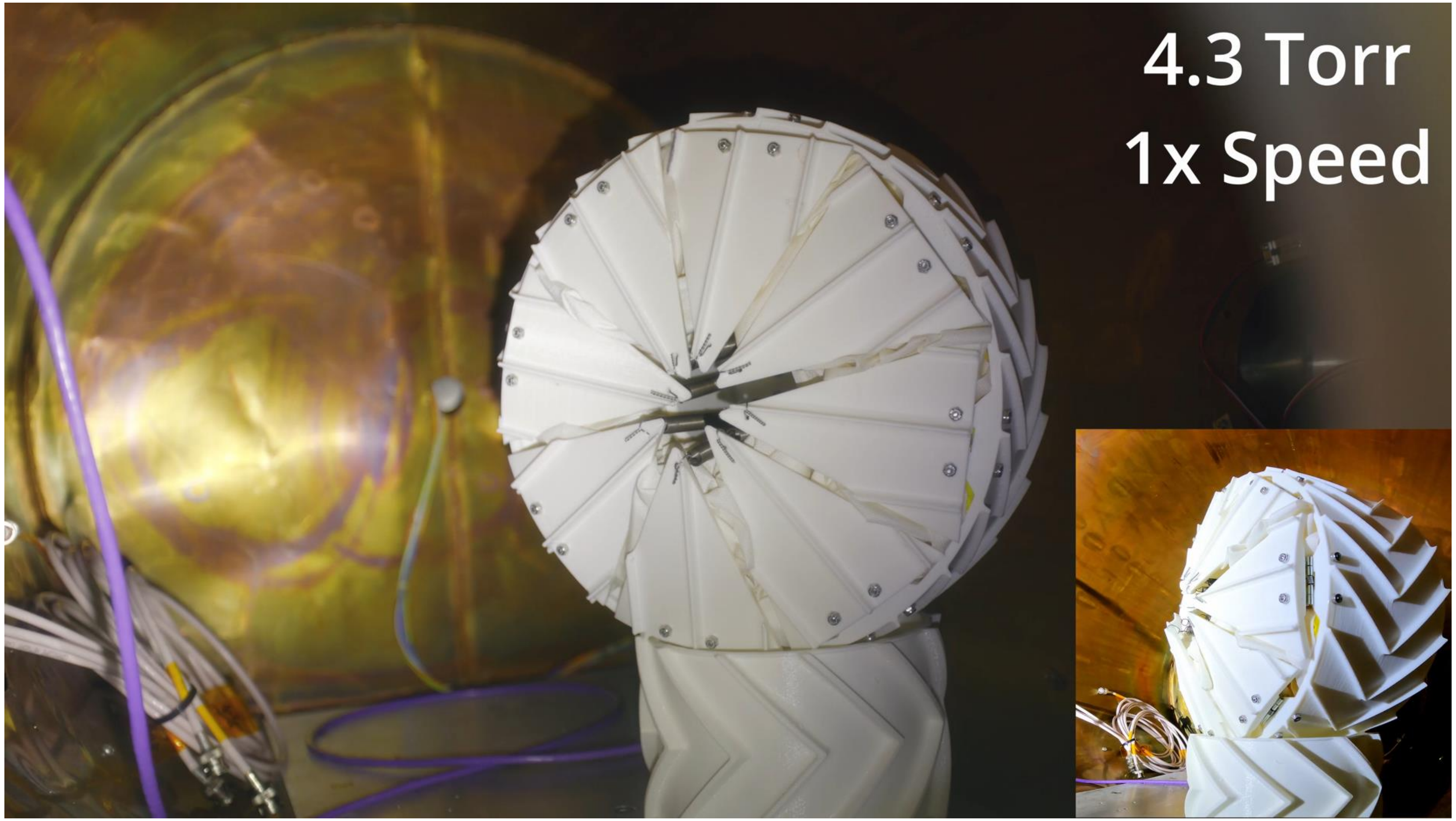
- Rover successfully rescued itself from loose, sloped soil via remote inflation.
- Four-wheel rover tests demonstrated visible performance improvement when hybrid wheel inflatable is deployed.

# Path to Flight

- Vacuum chamber deploy/retract test
- TRL 5!

(relevant environment)

- Reevaluation of material selection required for future



# Conclusions

- The AIRWHEEL project successfully demonstrates the concept of an inflatable wheel's ability to aid in rover self-extraction in loose regolith.
- As low as one inflatable wheel improves self-extraction but functions best when more wheels are deployed.
- Deployment and retraction actions are useful for variable terrain where a rigid OR flexible wheel performs best.
- The use of rigid petals improve traction and durability of soft goods of the hybrid rover wheel resulting in a smooth deployment and retraction.

# Acknowledgements

- Thank you to the whole team and Dr. Akin!
- And thank you BIG Idea Challenge for this opportunity!

## Auxiliary Inflatable Wheels for Lunar Rovers: The AIRWHEEL Project

NASA Big Idea 2024 Final Report

by

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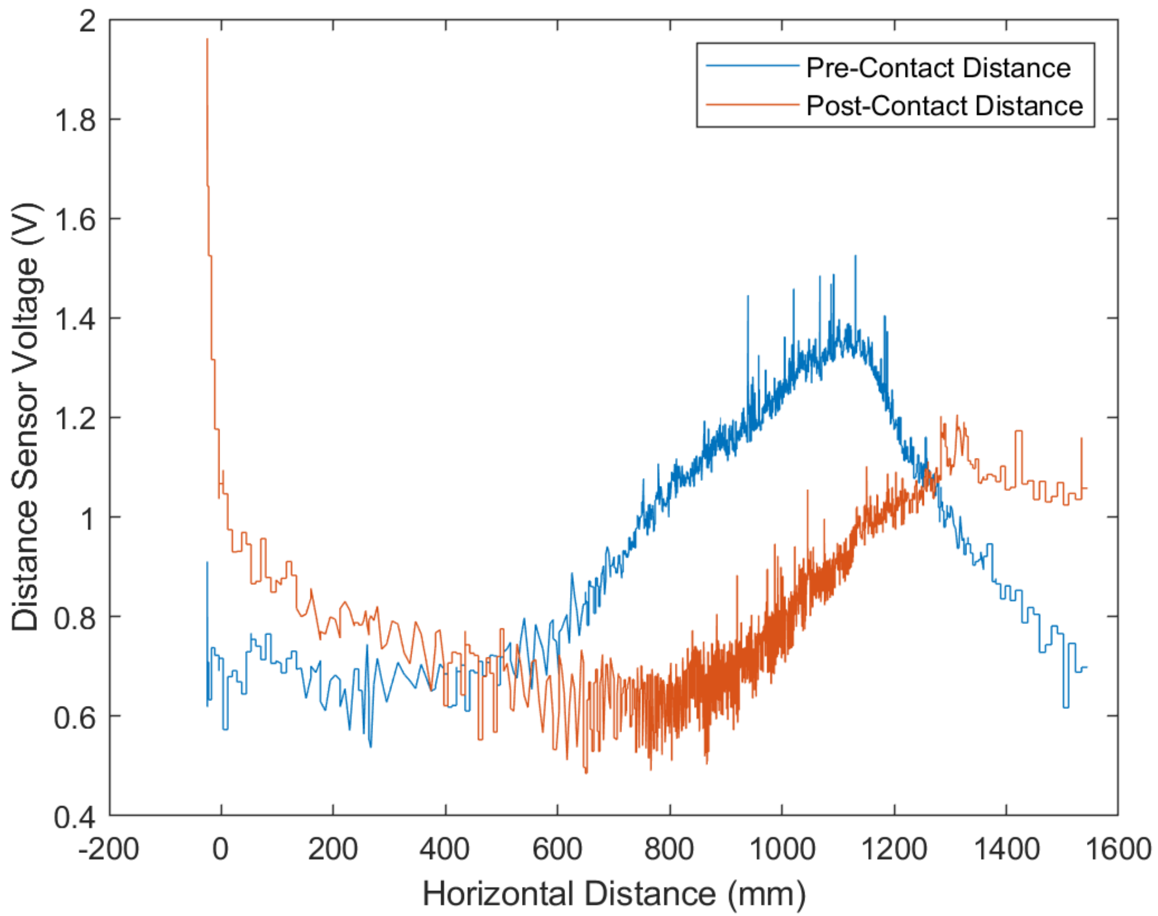
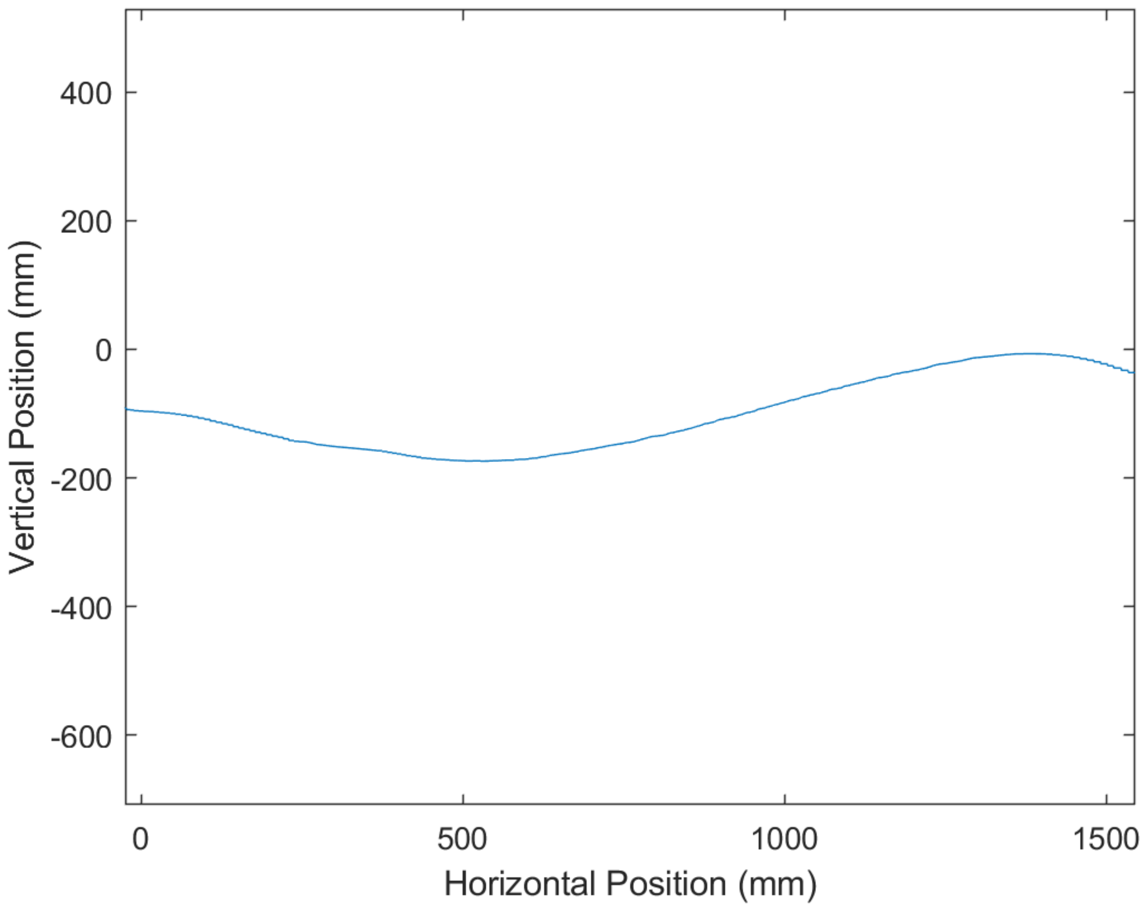
Supported by the Maryland Space Grant Consortium

# Appendix

# Ultrasonic Sinkage Sensors Unreliable




Measured soil height on either side of the wheel




Wheel travel path (hilly terrain)

# Force/Torque Oscillation, Off-Axis