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Cargo-BEEP:

Cargo Balancing Expandable Exploration Platform

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University of Michigan Big Idea Challenge


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Agenda

- Motivation
- Concept
- Mobility
- System Breakdown
- Materials

Summary

Cargo-BEEP is an inflatable rover that deploys from a compact cylinder to provide greater operational freedom for Artemis.

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Motivation

Figure 1: Key sites for Artemis transportation needs

[1] NASA

Planned Artemis Infrastructure

Lunar Terrain Vehicle (LTV)

- 10 year mission span
- Personnel Transport
- Designed for multiple missions

Pressurized Rover (PR)

- Personnel Transport
- Long-Distance Missions

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High Capability comes at a High Cost

Concept

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Concept of Operations

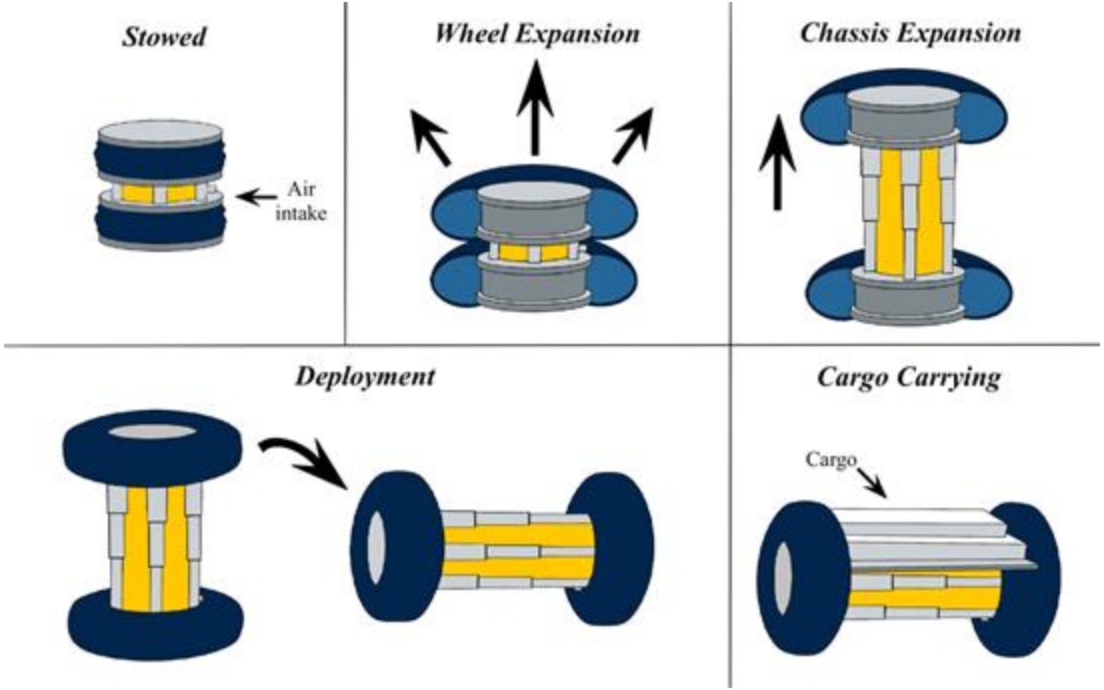


Figure 2: Fill and deployment procedure for Cargo-BEEP

Cargo-BEEP uses inflatables to deploy from a cylinder to a Segway-style cargo rover.

Volumetric Expansion Ratio: **1:5**

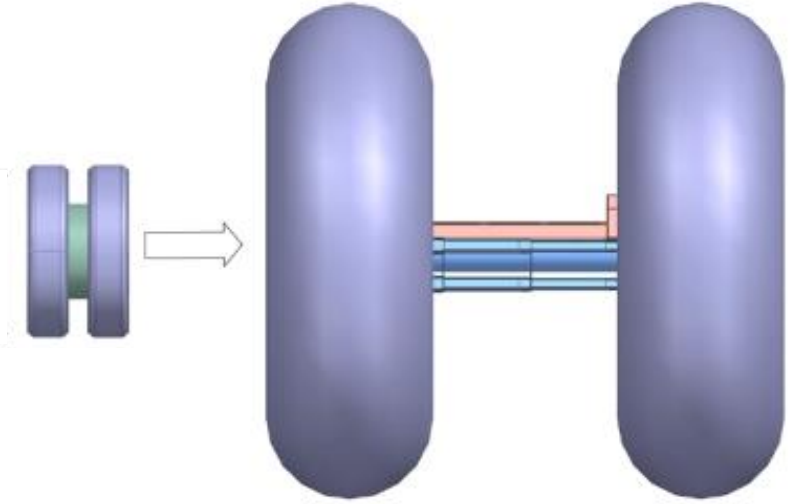


Figure 3: CAD image referencing compact size to fully inflated expansion.

Cargo-BEEP's Operational Requirements

Cargo Capacity	300 kg
Range	10 km
Environmental Resistance	Regolith abrasion, thermal variation
Operation	Autonomous, semi-autonomous, or remote-controlled
Deployment	Self-deployed via inflation
Additional Requirements	Reusability & operational adaptability

Cargo-BEEP's enables unique mission profiles.

- **Remote Control:** Deploy experiments in high-risk locations such as craters.
- **Semi-Autonomous:** Follow astronauts with heavy tools or equipment.
- **Autonomous:** Ferry materials between two crewed locations without astronaut intervention.

Mobility

Motion model exemplifies the inverse pendulum problem.

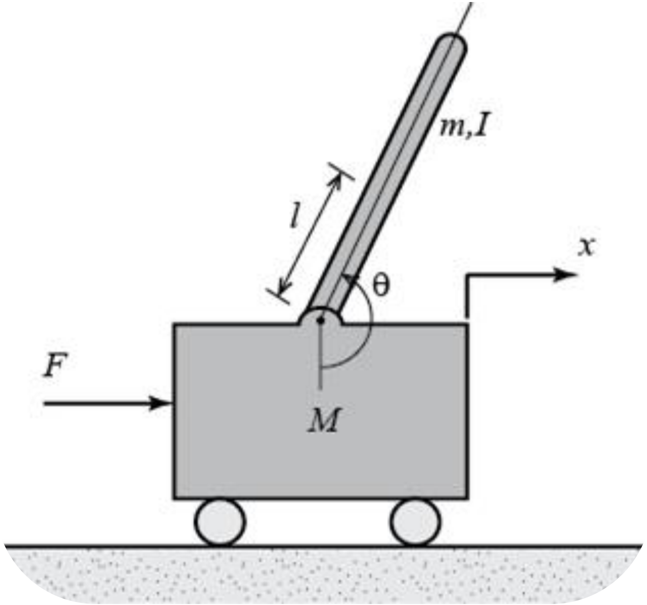
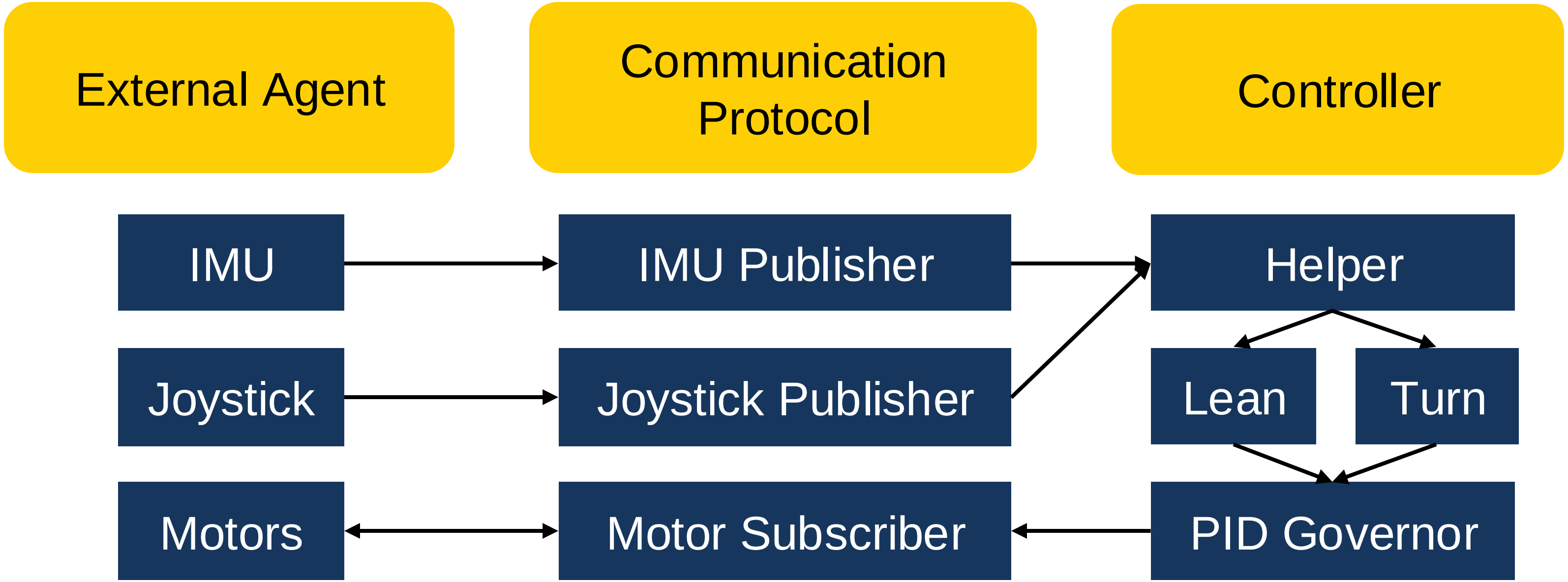


Figure 4: Physical model of the inverse pendulum. [3]

Figure 5: The described lean angle of a segway. [3]

Inverted Pendulum → Robust Control System


External Agent

Communication Protocol

Controller

IMU

IMU Publisher

Helper

Joystick

Joystick Publisher

Lean

Turn

Motors

Motor Subscriber

PID Governor

Figure 6: Rover Control Diagram

Figure 7: Controls Prototype operating
on rocky terrain

Figure 8: Controls Prototype driving on uneven terrain

System Breakdown

Cargo-Beep is made of multiple modular subsystems.

Wheel *Deployable Chassis* *Robotic Controls*

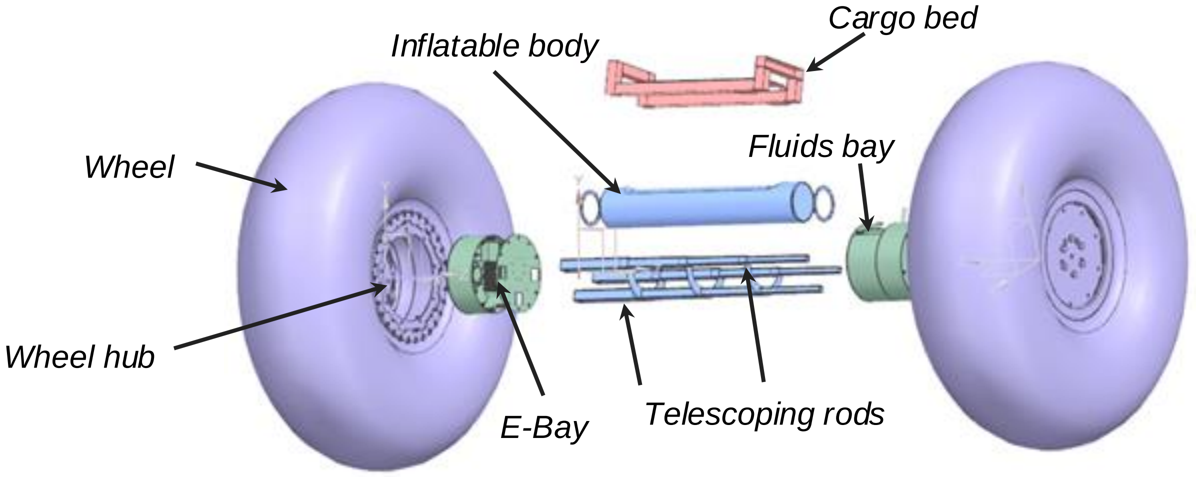


Figure 9: Expanded view of Cargo-BEEP systems

Inflatable wheels expand from a solid wheel hub.

Figure 10: Image of uninflated wheel

Figure 11: Fully inflated wheel

Chassis provides strength, rigidity, and drives expansion.

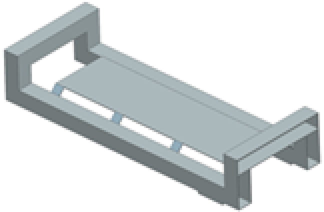


Figure 13: Cargo bed CAD design

Figure 12: Full chassis with inflatable body

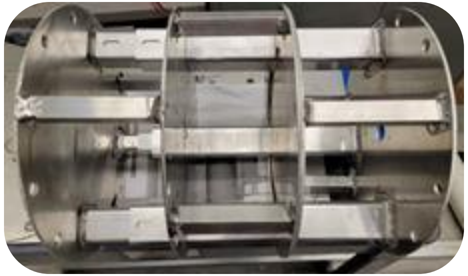


Figure 14: Chassis frame with the metal rods and brackets

Hermetic layer chosen to keep gas from escaping the inflatables.

Figure 15: Hermetic Layer of the wheel.

Figure 16: Hermetic layer of the body.

We used two types of seals to seal our hermetic layer.

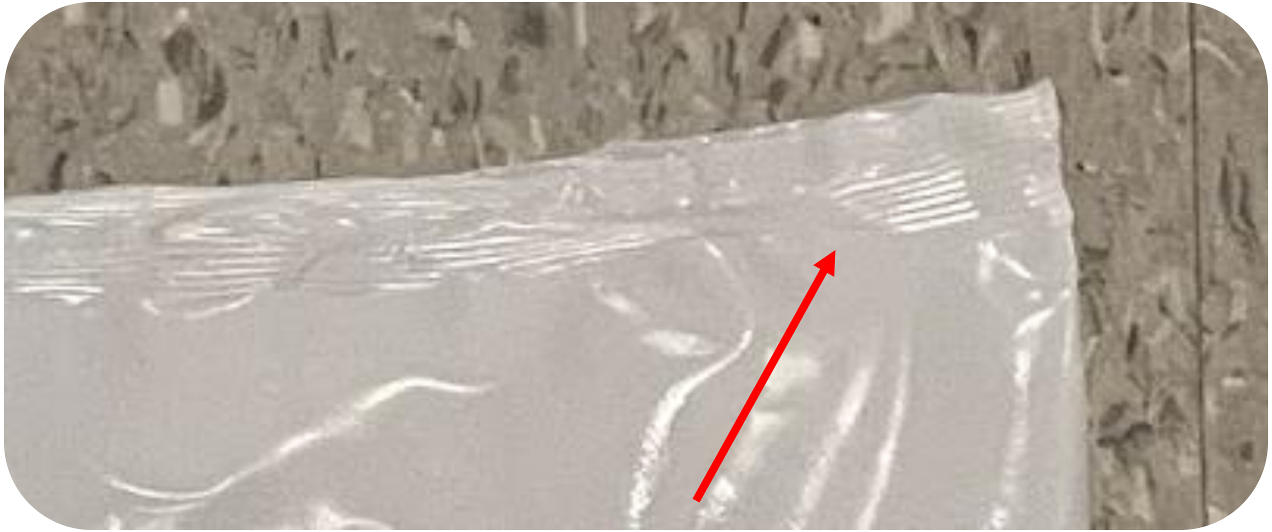


Figure 17: Fabric to Fabric heat sealed edge.

We used two types of seals to seal our hermetic layer.

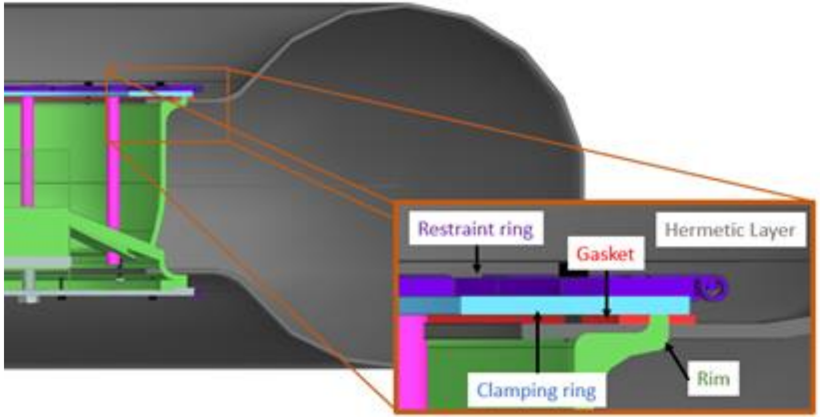


Figure 18: Wheel Gasket Diagram.

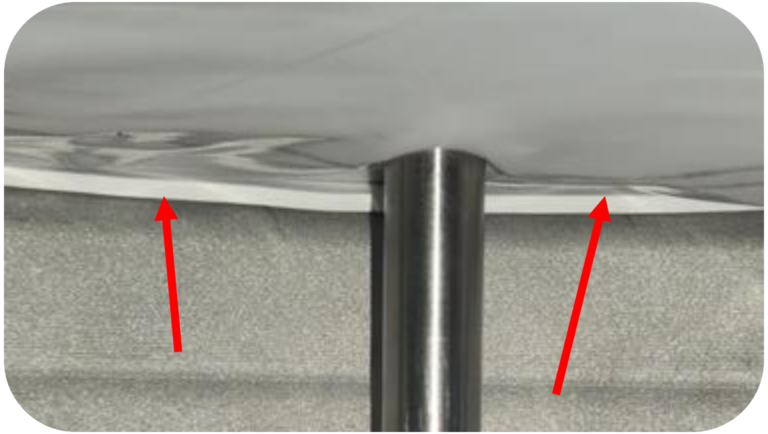


Figure 19: Fabric to Metal seal with PTFE Gasket.

Woven kevlar straps support pressure load.

Figure 20: 45 degree torus weave pattern woven around commercial off the shelf (COTS) scaffold.

Figure 21: 90 degree helical pattern.

Figure 22: Wheel restraint layer.

Abrasion from lunar regolith was assumed to be a high failure point.

Figure 23: Close-up of Abrasion layer on the wheel.

Figure 24: Wheel with full abrasion layer.

Cargo-BEEP inflates and deploys for use.

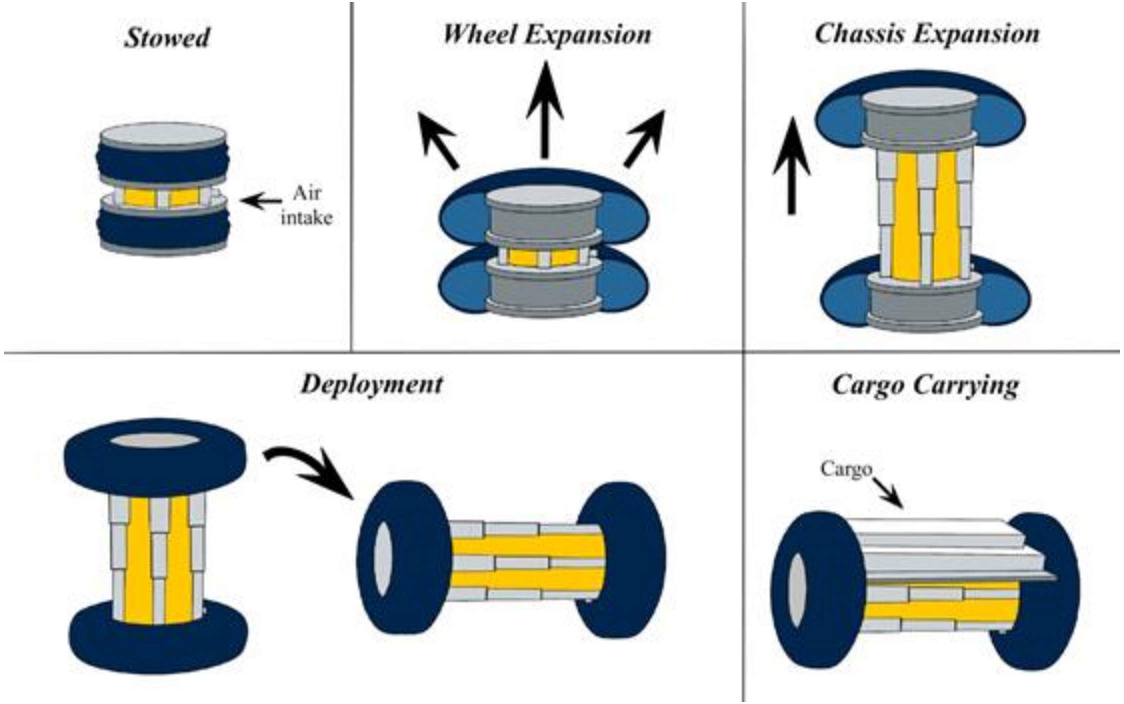


Figure 25: Inflation of the chassis.

Figure 26: Inflation of the Wheel.

Materials

System inflatables have many desired characteristics:

1. Be gas non-permeable
2. Maintain pressure
3. Control inflation and deflation
4. Prevent temperature fluctuations
5. Resist abrasion from lunar regolith
6. Resist degradation from UV radiation

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6. Resist degradation from UV radiation

Multi-layer solution required.

- **Consults:**
    - Virtual meetings with industry professionals.
- **Pending:**
    - Quotation requests and were not answered.
- **Denied:**
    - Companies were not willing to assist.

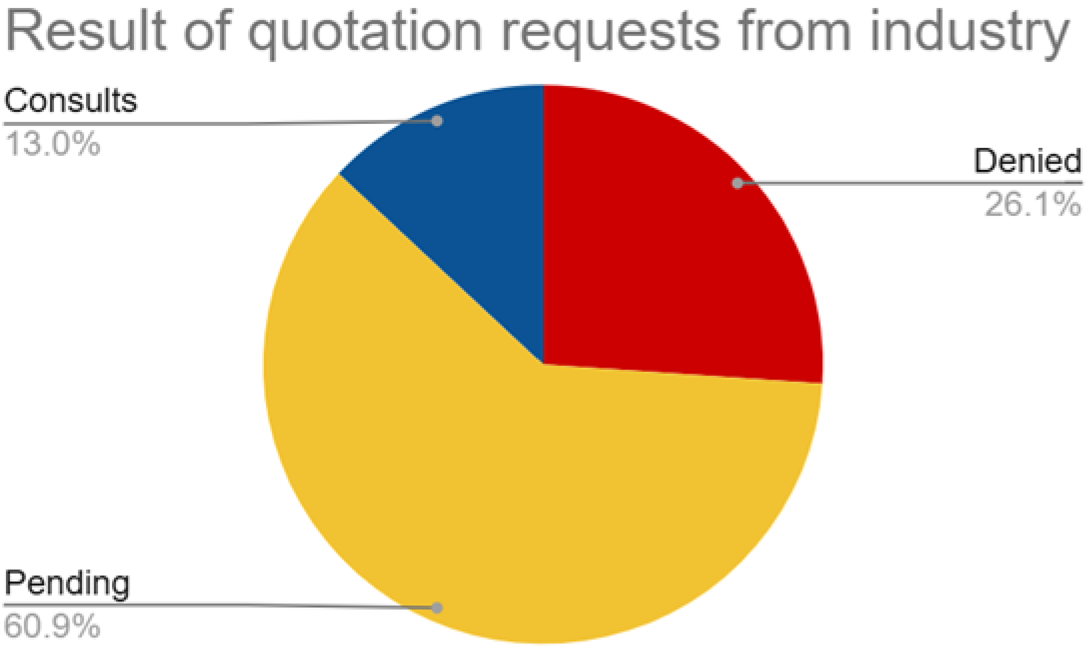


Figure 27: Resulting responses from industry.

Simulations allowed us to understand folding patterns. Folding patterns allowed predictions into where materials would need to vary.

Figure 28: Generated toroid shape.

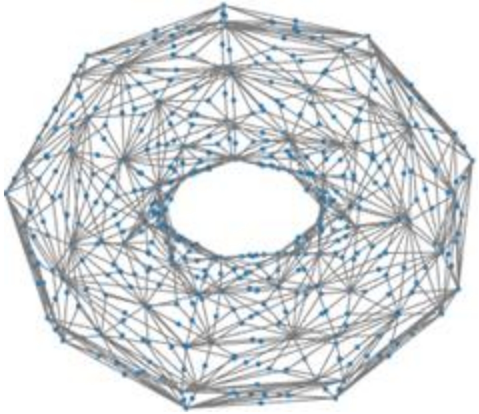


Figure 29: Generated fold locations from simulations.

Physical prototyping proved that designing any inflation controls was out of the scope of our project.

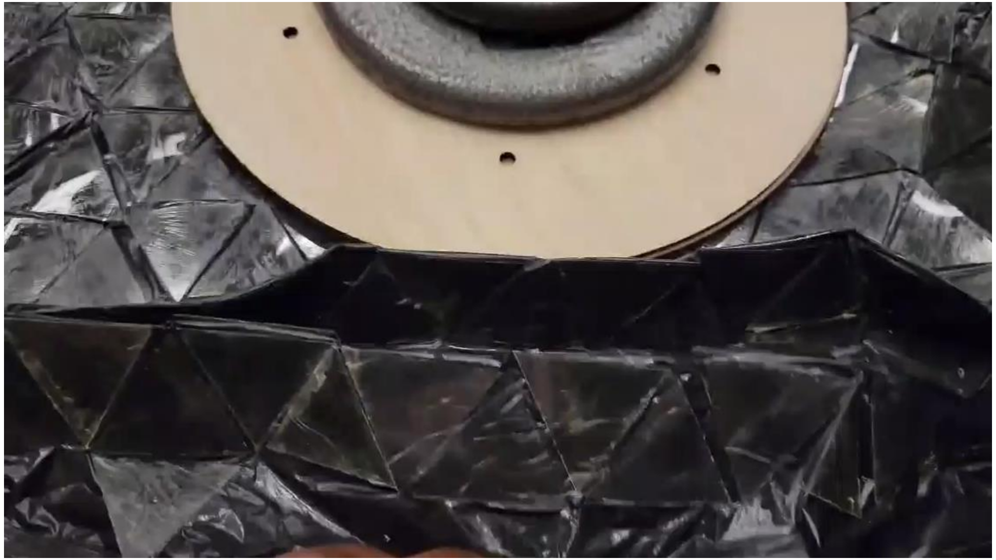


Figure 30: Motion dynamics of rigid and flexible material prototypes.

Preliminary inflatable body tests proved some feasibility towards using PET or other thermoplastics.

Figure 31: Initial PET inflatable prototype.

We encountered two large failure points when sealing the PET fabric.

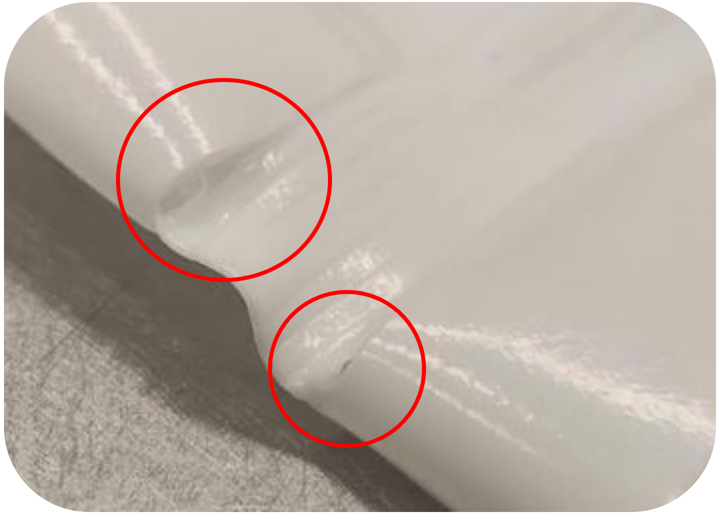


Figure 32: Too high of temperatures would cause the seals to break.

Figure 33: Metal brackets on the heat sealer created micro holes during sealing.

We were able to overcome this by makeshift patching the hermetic layer. It contained 20 psi when inflated.

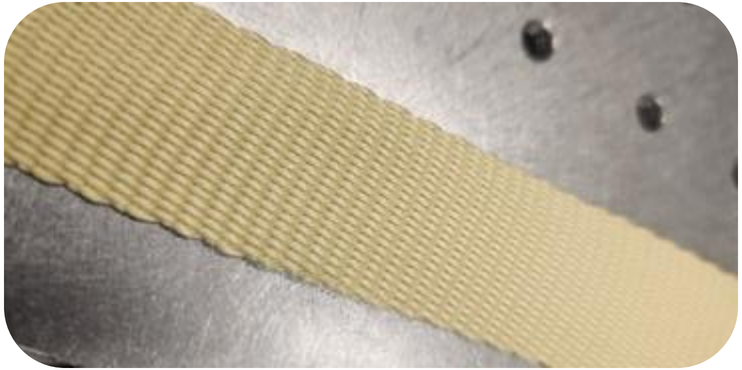
Figure 34: Patching on the hermetic layer

Figure 35: Inflated wheel with hermetic and restraint layers.

Using kevlar was a cheaper alternative that provided similar results.

Vectran:
Width: 1” Strips
Weave: Double Plain
Cost: $15.75/yard

Kevlar:
Width: 1” Strips
Weave: Plain
Cost: $7.85 / yard



Clevis roller inspired clamp design for weaving around 3D structures.

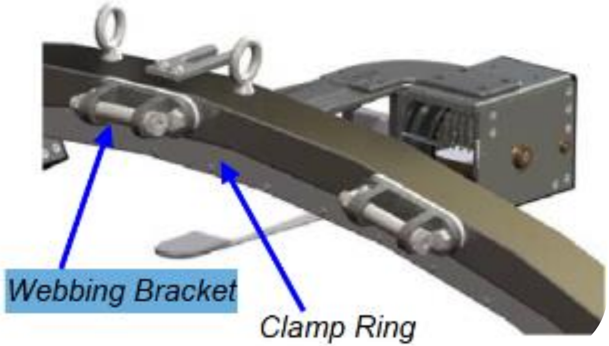
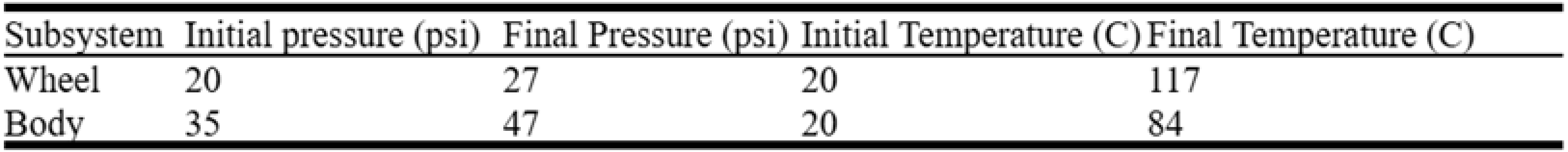


Figure 36: NASA design interface for strap attachment. [4]

Figure 37: Clevis roller inspired strap connections for restraint layer.

Thermal analysis confirms we do not need a thermal insulation for our inflatables.

- PET melts at temperatures between 235℃ and 260℃
- Electronics would require temperature mitigation but our inflatables would not.



Subsystem	Initial pressure (psi)	Final Pressure (psi)	Initial Temperature (C)	Final Temperature (C)
Wheel	20	27	20	117
Body	35	47	20	84

Table 1: Results from thermal feasibility analysis of wheels and body subsystems.

Kevlar and Vectran are extremely susceptible to abrasion.

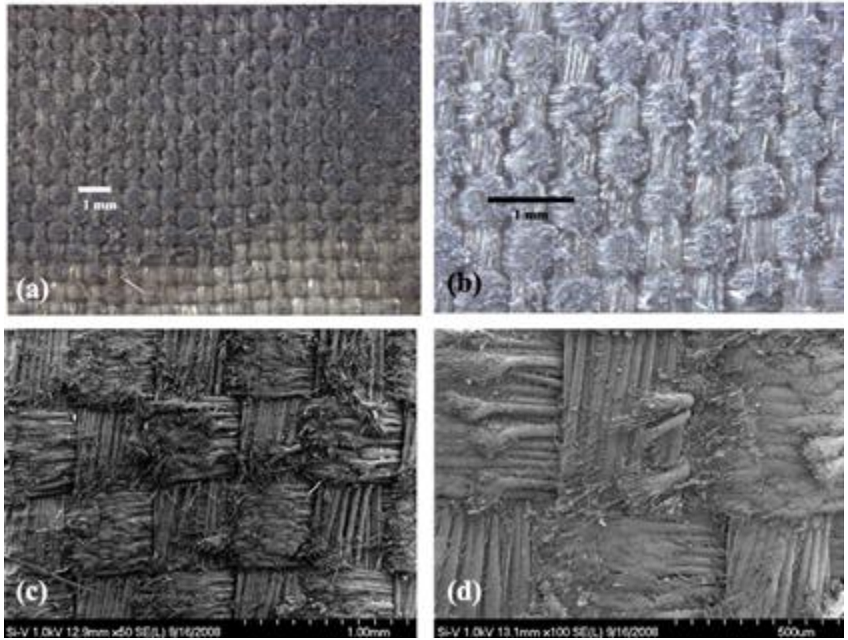


Figure 38: Vectran susceptibility to lunar regolith degradation. [5]

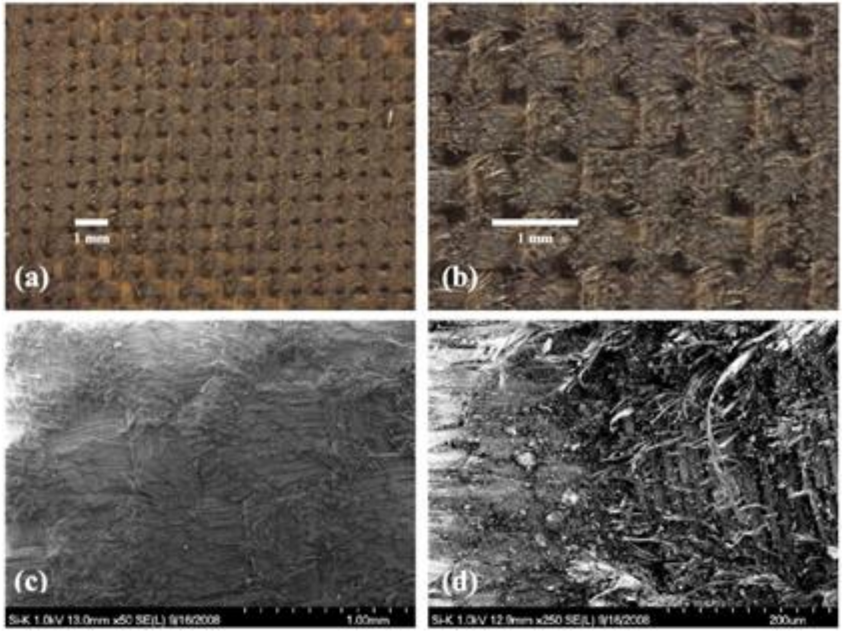


Figure 39: Kevlar susceptibility to lunar regolith degradation. [5]

Lunar regolith is incredibly abrasive.

- Regolith comprised of large range of particles sizes.
- No weathering on the Moon, highly jagged edges.
- Similar to driving on both glass and sandpaper.

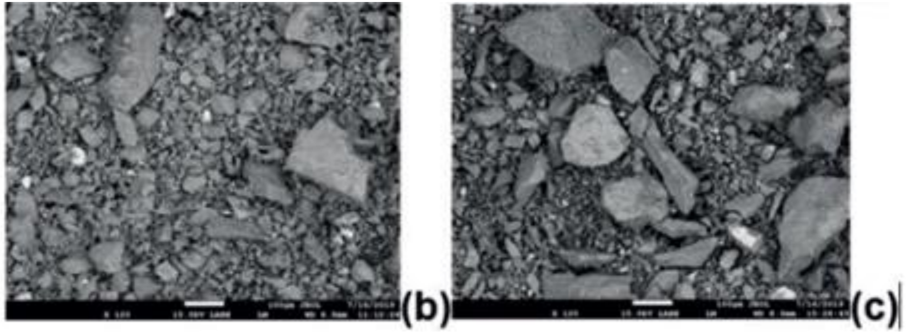


Figure 40: Images of Lunar regolith. [6]

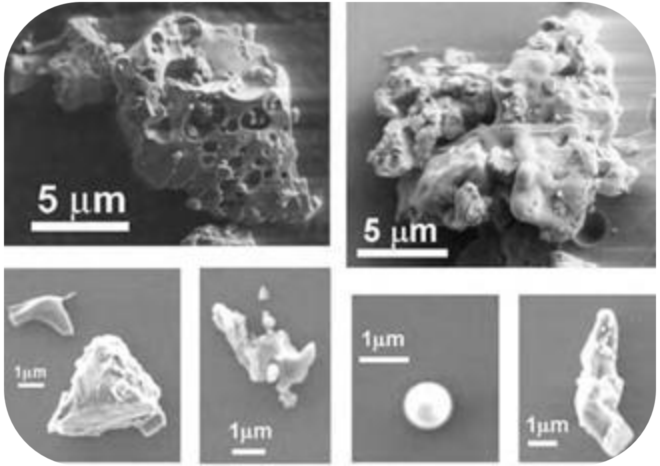


Figure 41: Microscope images of lunar regolith. [7]

Completed puncture testing showed that ballistic nylon was the strongest candidate for puncture resistance after vectran.

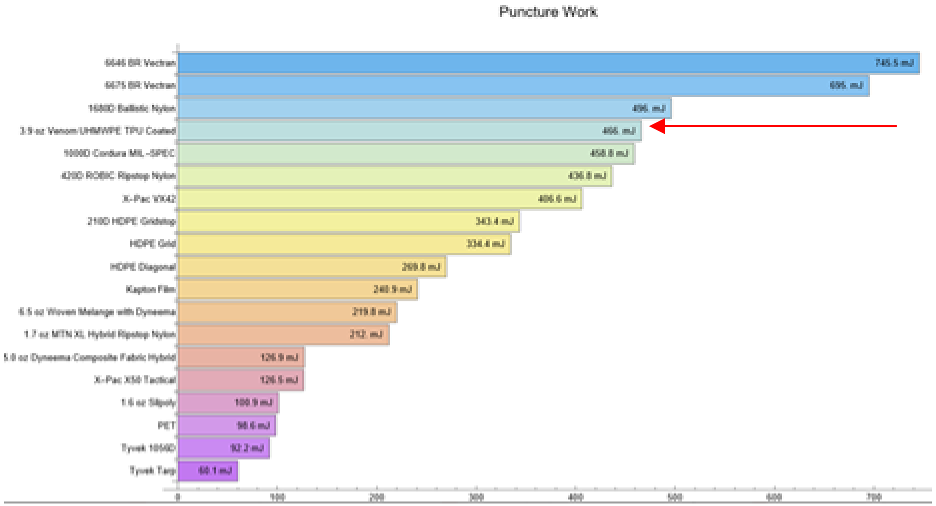


Figure 42: Puncture testing results.

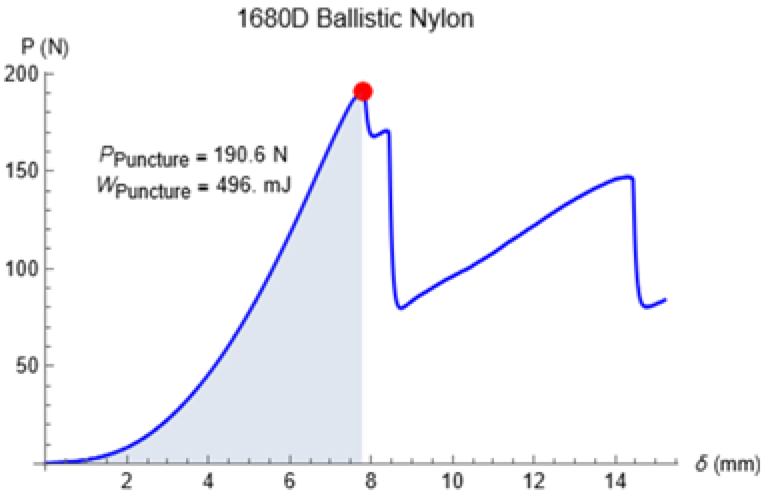


Figure 43: Microscope images of lunar regolith. [7]

Glossiness or reflectivity of the fabric provides additional UV resistance.

Figure 44: Ballistic Nylon is coated with Polyurethane, demonstrating the material’s glossy aspect.

Acknowledgements

Proposal

Dylan Trembla
Former team member, fluid mechanics & materials
Dr. Peter Washabaugh
Advisor for NOI, consultation on initial proof-of-concept
Prof. Mark Moldwin
MI Space Grant Consortium Director
Joanna Allen
Research Administrator for Proposal
Emma Gorbe
Former team member, material research and procurement

Phase 1

Rahul Nair
Former team member, thermal research
Rodney Rocha (JSC)
Consult on structural considerations
Professor Derrick Yeo
Informal advising and mentorship of the team on several occasions
Professor Xiwen Gong (Material Science Umich)
Consult regarding UV protection materials
Michael Flynn (Intuitive Machines - NASA)
Brief consult on risk matrices, potential future consultations on budget and schedule
Daniel Bernstein
Consult on materials for telescoping rods
Rahul Bapna (Anita Plastics)
Sample HDPE Provider
Yi Zhu
Consult regarding origami sim usage

Phase 2

Bally Ribbon Mills
Provider of low-cost samples of materials generally available only in bulk
Terry Larrow
Technician assisting with manufacturing and manufacturing-informed design
Andy Acosta
Material and Stress analysis consultation
Kyle Mitchell (Braksem)
Consult regarding material manufacturing
Forrest Sloan (Kuraray)
Consult regarding Vectran fiber manufacturing
Joe Pappas (Rocket Fiber)
Consult regarding fiber manufacturing
Ralph Schors (Albarrie)
Virtual Consult
Jared Roy
Manufacturing assistance
Margaret Kempe
Manufacturing assistance
Bethany
Controls prototyping

Stacy Dees & Janice Miller - Big Idea POCs

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Questions?

References

[1] “Lunar Mobility Drivers and Needs.” National Aeronautics and Space Administration , June 2024.

[2] Lunar Mobility Drivers and needs, https://www.nasa.gov/wp-content/uploads/2024/06/acr24-lunar-mobility-drivers-and-needs.pdf?emrc=b2dafa

[3] “Inverted pendulum: System modeling,” Control Tutorials for MATLAB and Simulink - Inverted Pendulum: System Modeling, https://ctms.engin.umich.edu/CTMS/index.php?example=InvertedPendulum&section=SystemModeling.

[4] “NASA Technical Reports Server (NTRS),” NASA, https://ntrs.nasa.gov/

[5] Abrasion of candidate spacesuit fabrics by simulated ..., https://ntrs.nasa.gov/api/citations/20090040698/downloads/20090040698.pdf

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[6] SEM images for EAC-1A (A) [75], lhs-1(b), and LMS-1 (c) [68]. | download scientific diagram, https://www.researchgate.net/figure/SEM-images-for-EAC-1A-a-75-LHS-1b-and-LMS-1-c-68_fig4_341990794

[7] (PDF) micro-morphology and toxicological effects of lunar dust, https://www.researchgate.net/publication/259325023_Micro-Morphology_and_Toxicological_Effects_of_Lunar_Dust

Gas Selection: Argon or N2

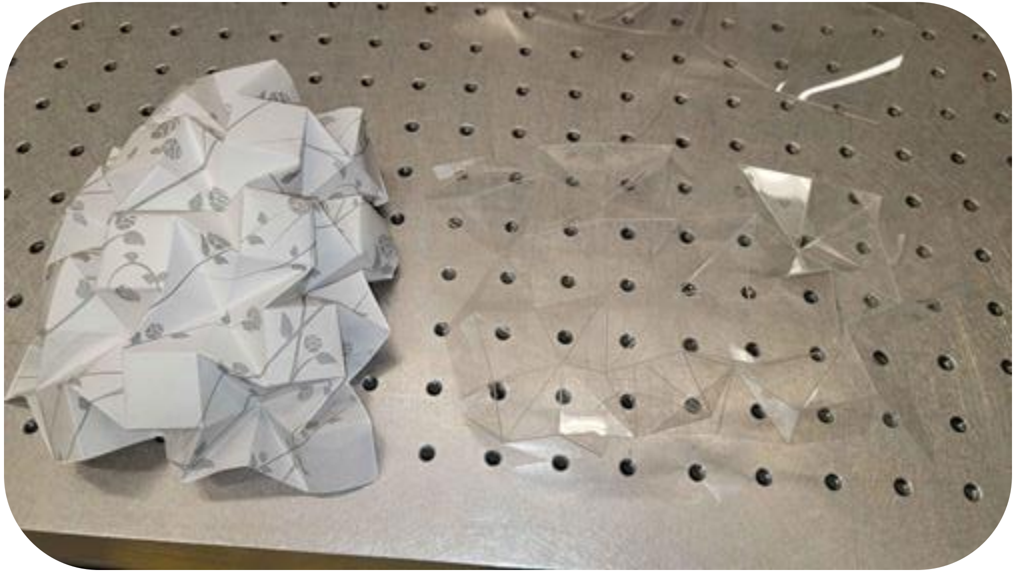
Argon

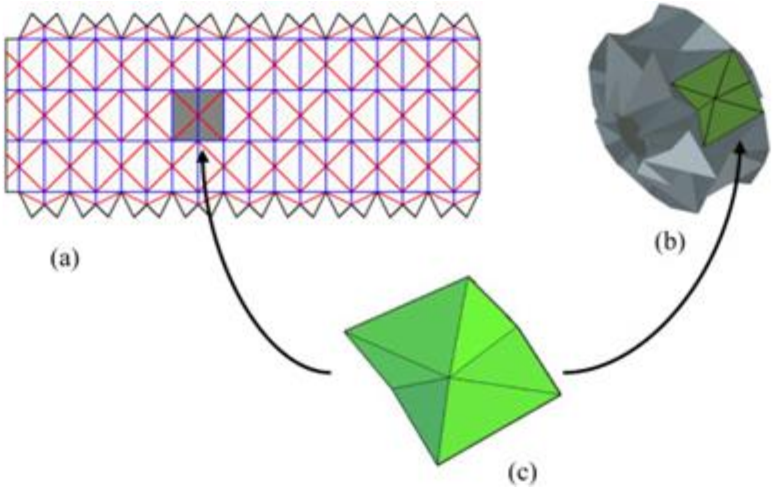
- More inert than N2
- Superior insulator
- Less reactive to temperature
- Less reactive to radiation

Nitrogen

- Inert and commercially available
- Safer to handle than Argon
- Inexpensive
- Readily available

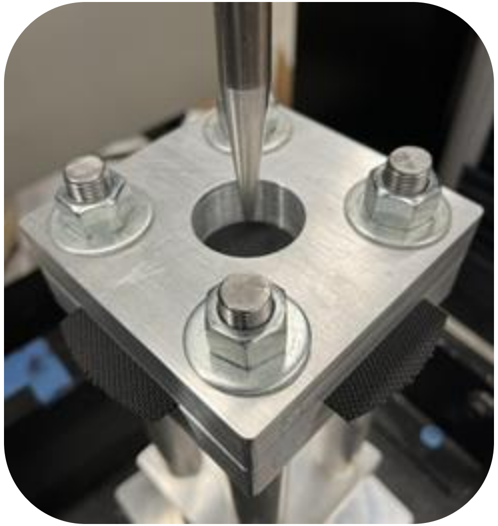
More traditional origami techniques improved flexibility, but still restricted initial package size.





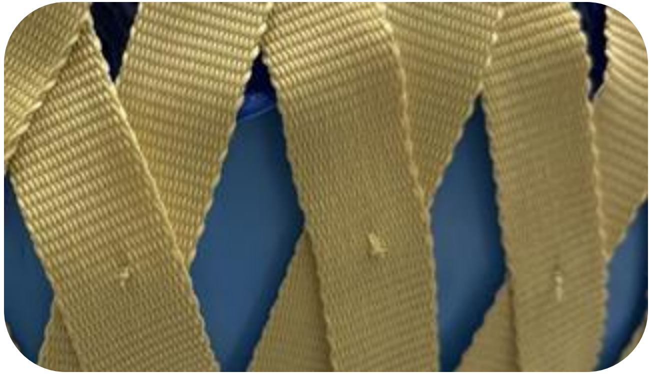
https://www.sciencedirect.com/science/article/pii/S0020746220301955

Puncture testing was designed and completed in accordance to ASTM - F1306-21



We used two different stitch types to connect the straps together.

We used a tapered diamond stitch to attach new straps to the ends of other straps.



Strips stitched at crosses to prevent torsional slip.

Structural Analysis

Cargo load	Max. Stress	Max. Displacement
300 kg (500 N)	56 MPa, concentrations at standoffs on e-bay and motor shaft	0.5 mm at cargo bed
500 kg (812 N)	120 MPa, concentrations at s standoffs on e-bay and motor shaft	0.8 mm at cargo bed
1000 kg (1625 N)	160 MPa, concentrations over 70 MPa on body, edges around cutouts for rods in e-bay face, standoffs, and motor shaft.	1-2 mm at cargo bed

Table 4. Maximum stress and deflections of the cargo bed for various cargo configurations. As the cargo bed is elastic and its stiffness is driven by pressure, the displacements are inaccurate.