# Cargo-Balancing Expandable Exploration Platform (Cargo-BEEP)

## A Low-Cost Semi-Autonomous Lunar Transportation Platform

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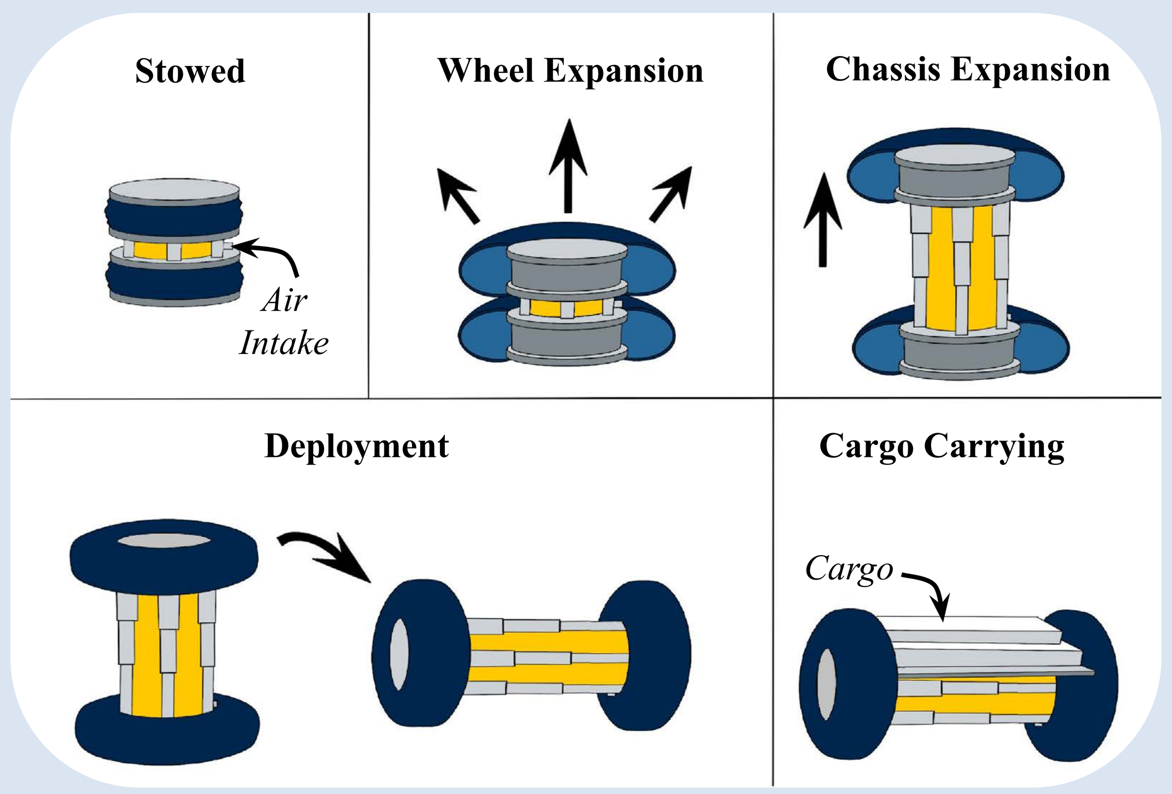
## Motivation

Cargo-BEEP is a two-wheeled inflatable semi-autonomous rover. It is compact when stored and capable of transporting 300 kg of cargo over distances up to 10 km. Cargo-BEEP provides low-cost, low-weight exploration and transportation capabilities where utilizing larger, more expensive vehicles would be too risky or logistically complicated. The compacted form of Cargo-BEEP can be carried by larger rovers, increasing the operational freedom of lunar excursions. Additionally, Cargo-BEEP can easily be adapted in-situ to carry other payloads, such as cameras and experiments for exploratory missions.

**Use Cases**

- *Follow* astronauts with heavy tools or equipment.
- *Deploy* experiments and gather data in high-risk locations such as craters.
- *Ferry* materials between two crewed locations without astronaut intervention.

## Concept of Operations




1. Position rover on wheel-hub
2. Inflate Cargo-BEEP through fill port using an external gas supply
3. Wheels expand first for stability, then chassis deployment mechanism inflates and separate the wheels
4. Push Cargo-BEEP over so both wheels are on the ground (it doesn't mind!).
5. Mount cargo-bed and load up to 300 kg of cargo.
6. Set to one of three control modes:
   a. Remote Control: Astronauts can directly control Cargo-BEEP for exploratory missions
   b. Semi-Autonomous: Follows astronauts with tools, experiments, samples, or other cargo.
   c. Autonomous: Ferries resources to and from pre-set waypoints.

## References

[1] VALLE, G., IITTEKEN, L. and JONES, T. (2019) . *NASA*, 20190000847
[2] FORD, C. and NILSSON, L (1956). SAE, 560193
[3] FUENTE, H., et al. (2000). *AIAA*, 1822

## Innovations

**Inflatable Body**

- Deployment of semi-rigid dynamic structures using inflatables (chassis deployment). Transferable to deployment of landers, rovers, and satellites from compact configuration.
- Inflatables as load-bearing structures, transferable to inflatable habitats and future vehicles.

**Wheel**

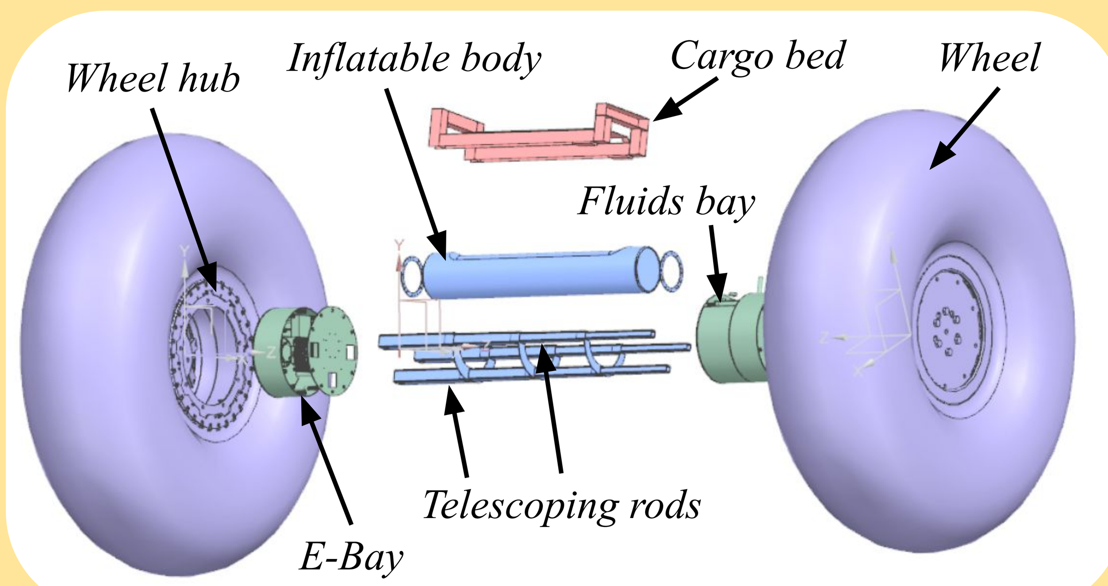
- Application of inflatable wheels in lunar environments.
- Low-mass 3-layered tire with hermetic, restraint, and anti-abrasion layers to provide durability and collapsibility.
- Collapsible wheels to reduce storage size: wheels inflate to 3x original diameter

**Controls**

- Control of two-wheeled self-balancing vehicle on non-rigid wheels on lunar-like terrain.

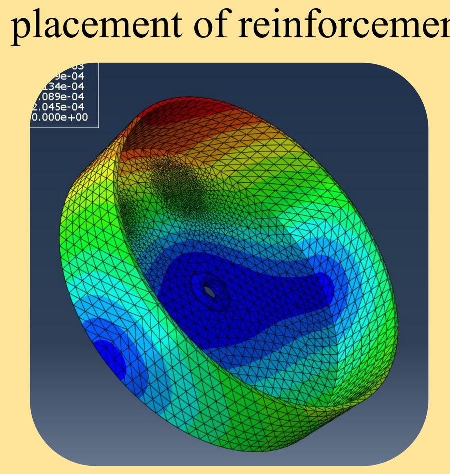
## Design & Theory

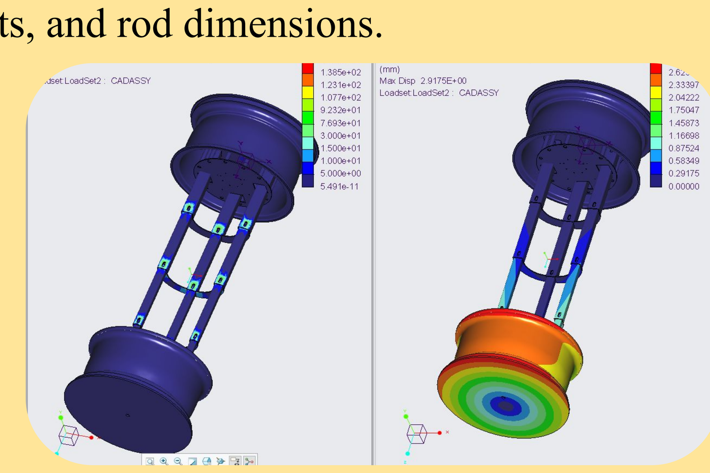
The overall system consists of two inflatable wheels connected via motor shafts to an expandable chassis. The inflatable center body drives the expansion of the chassis and supports the cargo bed. The telescoping rods provide torsional rigidity. A cargo bed is attached post-deployment to carry equipment, samples, and more.




**Structural validation**

FEA was used to validate the integrated system against static twisting and loading, with safety factors of approximately 2.5 and 3, respectively. Structural failure would likely occur at fabric seams (as observed in testing), rod pins, or rod/chassis interfaces. FEA and torsion calculations were used to determine material thickness, bolts sizing, placement of reinforcements, and rod dimensions.



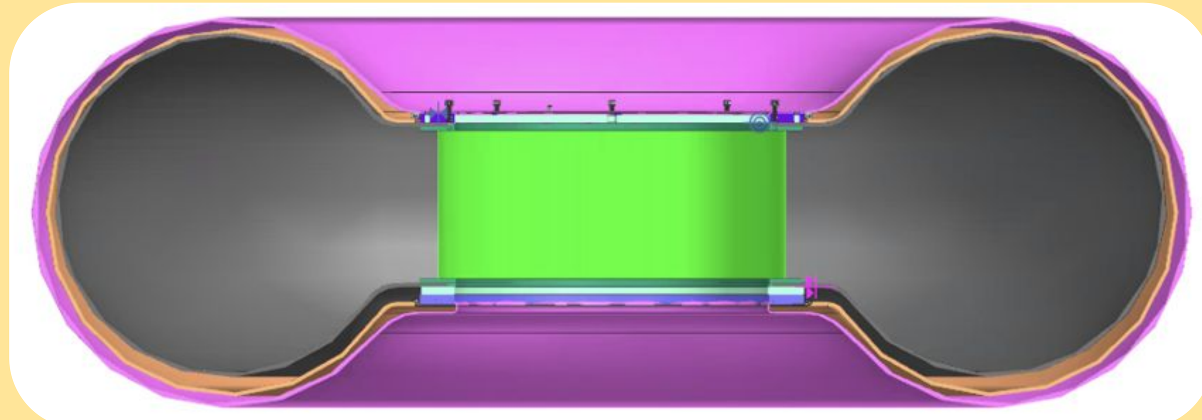


**Thermal validation**

Cargo-BEEP would operate in illuminated conditions due to thermal constraints of the batteries. A worse-case thermal analysis over 10.5 hours resulted in final temperatures of 117° C for the wheels and 84° C for the chassis and electronics. This would be tolerable with reasonable material selection and insulation for electronics.

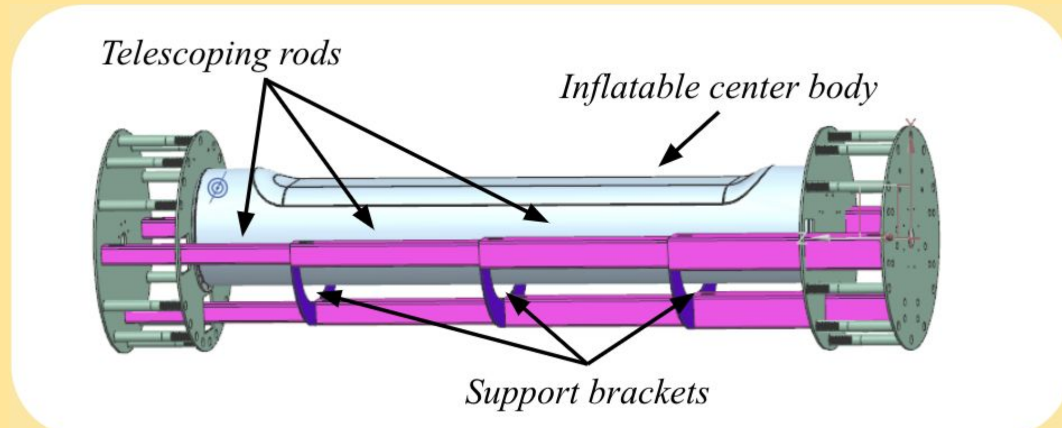
## Inflatable Wheel Subsystem

Cargo-BEEP's wheels utilize flight-proven inflatable softgoods technology [1] based on ground-proven off-road tire designs [2]. Designed to inflate to 1.5 m, the low-pressure and high-surface-area design prevents slip and minimizes puncture risk on extreme terrain. For our prototype, we created a 2/3rd scale model. The wheels consist of three layers: The hermetic layer acts solely as a gas barrier, the restraint layer holds pressure and bears loads, and the anti-abrasion layer protects against lunar dust and terrain. Testing suggests that treads are optional but may improve performance.



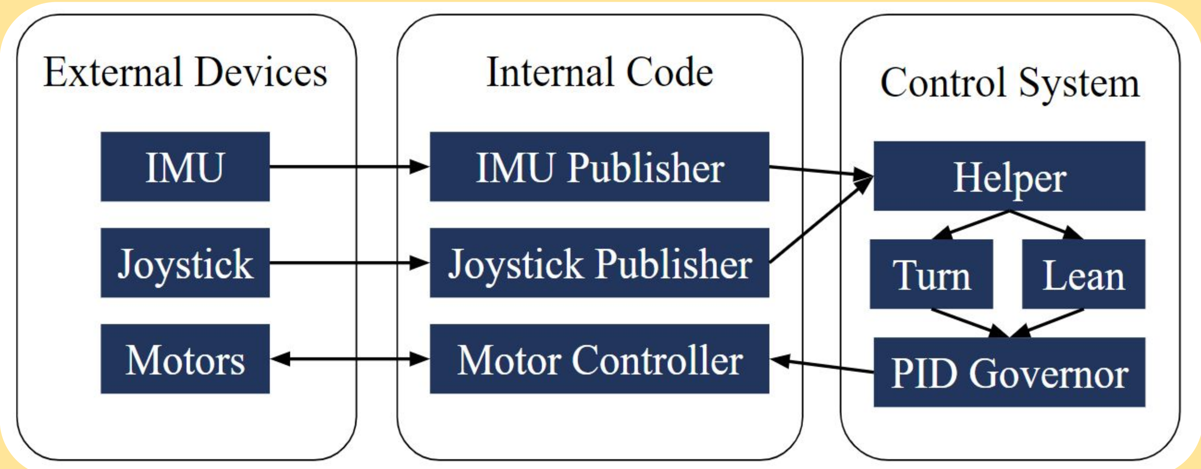
## Deployable Chassis Subsystem

An inflatable body, similar in construction to the wheels, drives expansion of the deployable chassis from the stowed state and bears the weight of the cargo. Torsional stiffness is provided by a set of three collapsible rods which also serve as mounts for a cargo bed. Our prototype has a 2.8:1 linear expansion ratio, but could easily be modified to fit different requirements. The locking mechanism of the rods and cargo bed require minimal astronaut effort.




## Electronics and Controls Subsystem

Cargo-BEEP tackles the inverted pendulum problem with a dual-PID control system to account for the unique dynamics of inflatable wheels on lunar terrain. The PID Governor regulates and prioritizes the two PID control systems based on tuning variables. The first system controls the lean angle for the chassis, accelerating and balancing the cargo bed. The second system controls the turn angle for the robot. The controls prototype was tested successfully on rocky sandy surfaces, scaling hills with a grade of 45° and using only 25% of the maximum power.




## Verification Testing

**Wheel Deployment:**

Wheels inflated fully to 35 psi. Cycle testing revealed issues with our sealing method for the hermetic layer. This is solvable with improved sealing techniques or selection of an alternate hermetic material.

**Chassis Deployment**

Prototype expandable chassis successfully deployed with the inflatable body, which faced similar sealing challenges.

**Material Selection and Testing**

*Hermetic Layer:* PET was selected for its low permeability and was used on our prototype. We experienced persistent leakage issues at seams of our inflatables. A new heat-sealing method is required, but softgood hermetic layers have been successfully implemented in space technology demonstrations [1][3].

*Restraint layer:* Kevlar was successfully implemented in prototypes for a restraint layer, but Vectran should be used in a flight model for better flexibility and reduced creep [3].

*Abrasion layer:* UHMWPE-based Venom and Ballistic nylon were the highest performing in puncture, slash, and abrasion testing of 19 candidate materials. Ballistic nylon was chosen due to flight history and better temperature performance

**Controls Testing**

*Wave Field Testing:* Successfully cleared several 45° hills in a row and maintained balance for the cargo bed.
*Mars Yard Testing:* Successfully maintained balance and performed complex turns to navigate rugged simulated mars terrain.

## Future Work

- Full integration with each of the subsystems (Wheels, Chassis, Controls)
- Reconsider material and sealing methods for the hermetic layer
- Temperature-controlled vacuum chamber testing
- Implement automatic locking mechanism in telescoping rods
- Complete traction testing on broader selection of treads
- Autonomous controls and path-finding (A* is a standard path-finding algorithm in the robotics industry and computer vision would provide localization)
- Kalman filters and higher quality IMU for more accuracy