Autonomous Surface Mobility on Small Solar System Bodies

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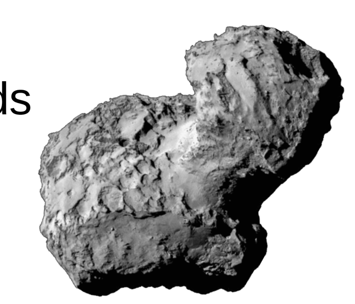
Exploring Small Bodies

Small Bodies such as comets, asteroids, and irregular moons are high priority targets for NASA and other space agencies worldwide. They are key stepping stones for human exploration of Mars and beyond, and their undisturbed surfaces allow scientists to peer into the early history of the Solar System. However, little is known about their chemical and physical properties.

Problem

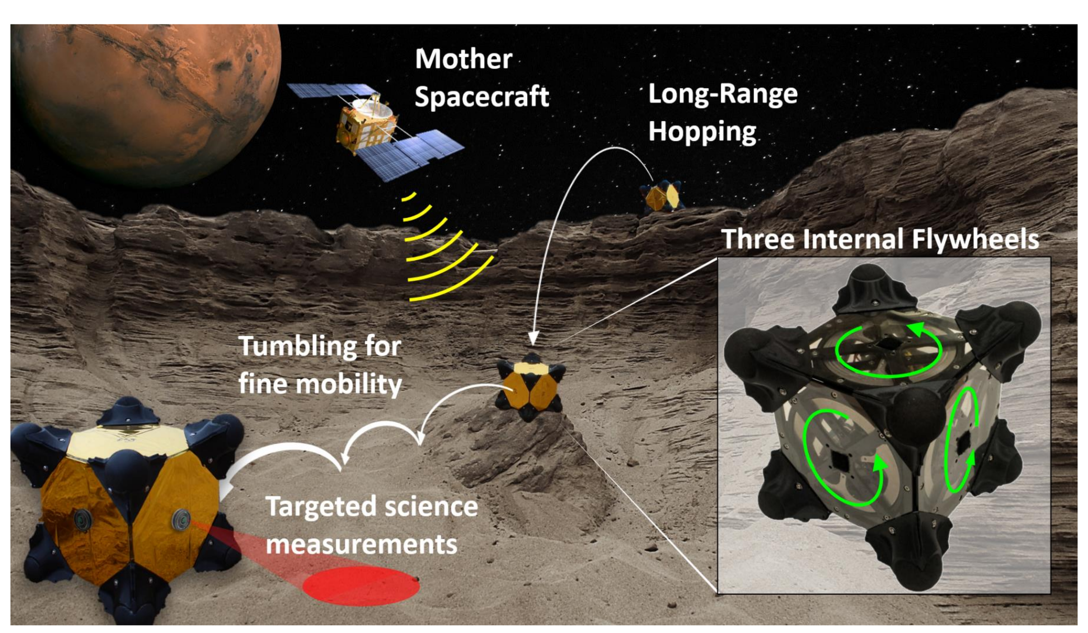
Robotic exploration of small bodies presents many new challenges beyond our experience on the Moon and Mars:

- Irregular shapes and gravity fields
- Extremely **weak gravity**
- Highly uneven surfaces
- Dust environment



Hopping Rovers

Meet **Hedgehog**, a minimalistic spacecraft/rover hybrid that uses internal actuation to *controllably* hop and tumble across the surface.

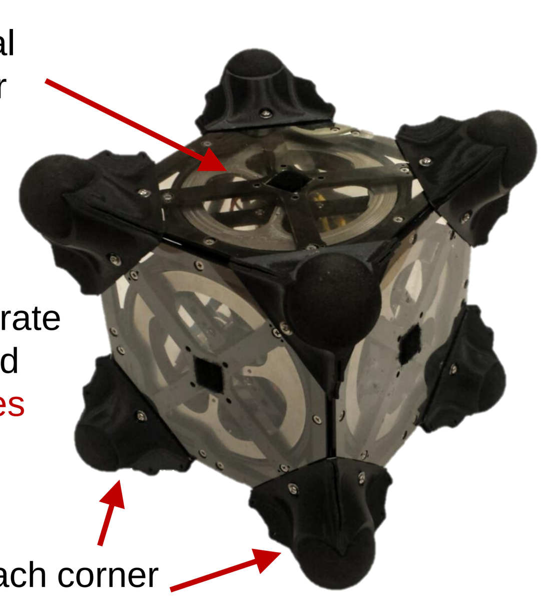


Mobility Components

Three internal **flywheels** for mobility

Motors and **brakes** generate controlled and abrupt **torques** on flywheels

Spikes on each corner protect from terrain and act as feet for hopping



Key Features

Mechanically and thermally **sealed** from environment

Symmetric design allows mobility in any orientation

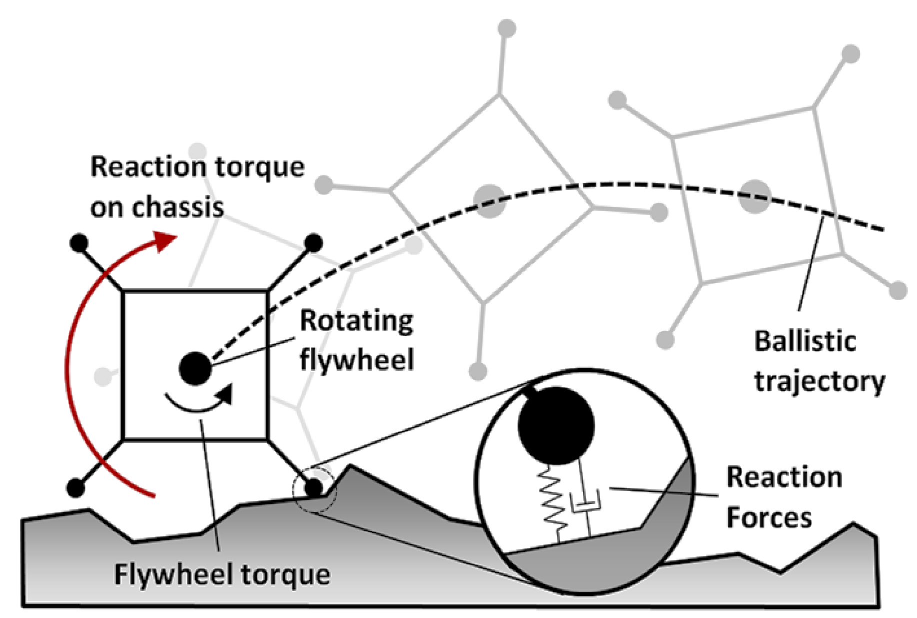
Large internal volume for **scientific payload**

Minimalistic

Scalable

Mobility via Internal-Actuation

Key idea: Swapping angular momentum



Spin up flywheels to desired speed

↓

Apply mechanical brakes with large torque

↓

Angular momentum transferred to chassis

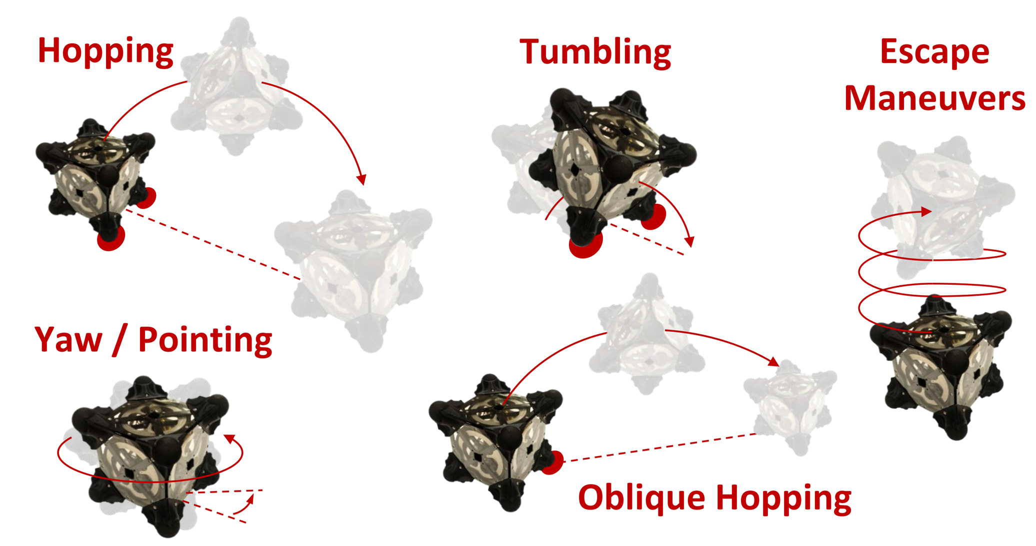
↓

Reaction forces of spikes on the ground

↓

Rover hops in a forward ballistic trajectory

Three orthogonal flywheels allow for angular momentum in any direction. This can be leveraged to enable multiple modes of mobility:



Control and Autonomy

For missions to distant bodies with delayed and intermittent communication, rovers need to autonomously navigate to targeted locations. Analogous to playing a game of golf, this requires an iterative sequence of controlled maneuvers that achieve incremental progress. This consists of four main phases:

Localization: where am I?

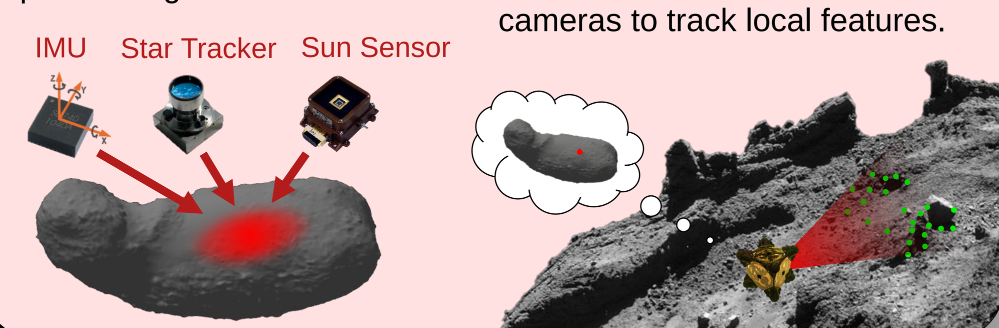
First, Hedgehog must estimate its location on the surface, which is challenging without GPS. Our approach is divided into two phases:

Coarse / Global Estimation

Inertial and optical sensors provide regional localization.

Fine / Local Estimation

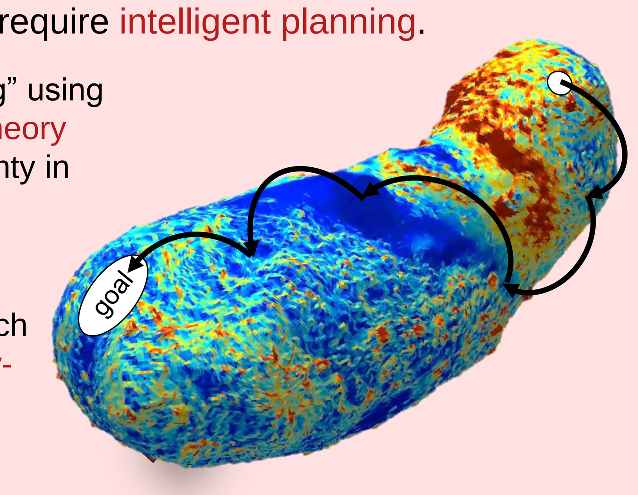
"Visual Simultaneous Localization and Mapping" (VSLAM) uses cameras to track local features.



Planning: where should I go?

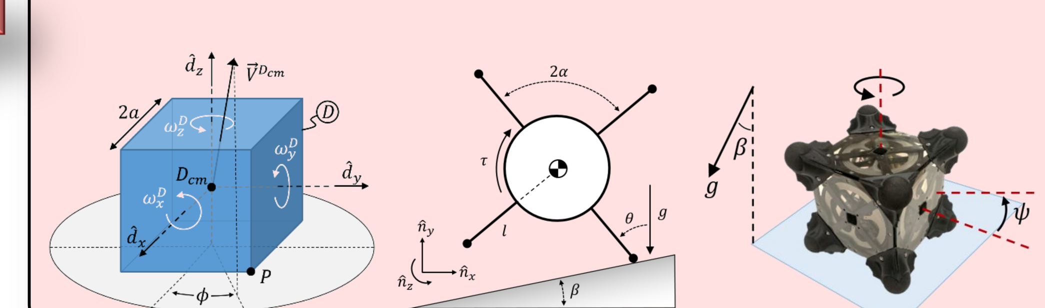
Choosing a desired hopping trajectory isn't always as simple as "go towards the goal." Steep slopes, strange gravity fields, and hazards in the environment (e.g. pits, boulders, cliffs, etc.) require intelligent planning.

- "Closed-loop planning" using sequential decision theory accounts for uncertainty in the environment.
- A control policy is computed offline, which produces fast, energy-efficient, and safe trajectories.



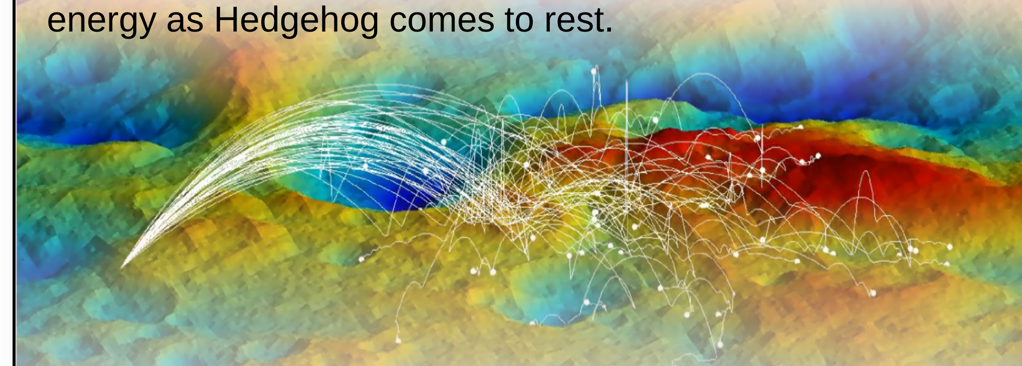
Execution: How do I get there?

Several analytical and numerical models were studied to derive flywheel control laws, which map a desired launch vector to flywheel speeds. These control laws are functions of Hedgehog's geometric and inertial properties, the local gravity field, and local surface properties. Simulations and experiments suggest a motion accuracy of about 10%.



Ballistic Flight: hanging on for the ride!

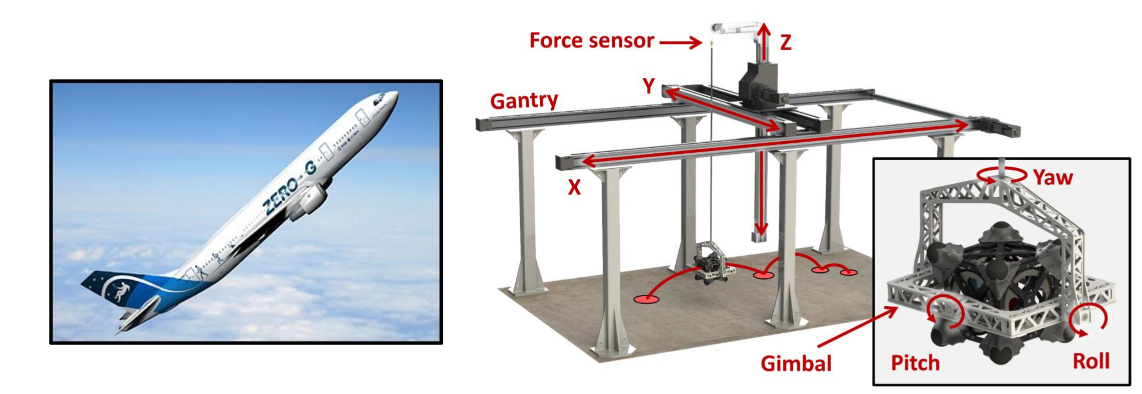
Once in flight, Hedgehog can use its flywheels for attitude stabilization, but otherwise has no control over the resulting trajectory. A series of random bounces dissipate kinetic energy as Hedgehog comes to rest.

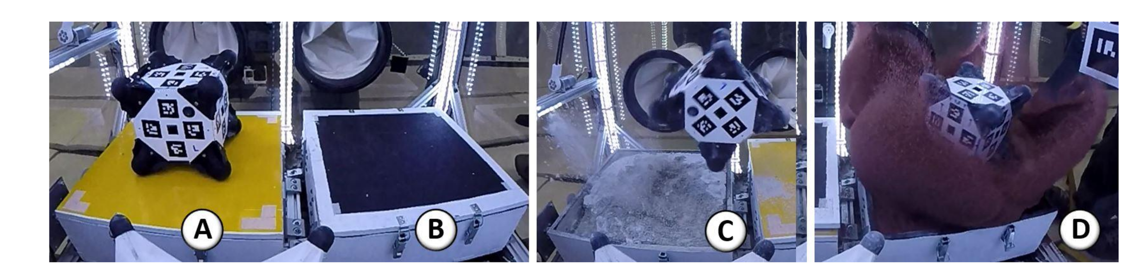


While damping strategies can mitigate large rebounds, the planning phase also accounts for highly stochastic bouncing.

Experiments

Reduced-gravity Experiments





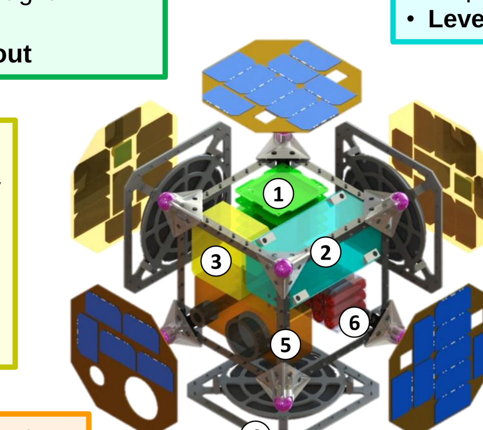
System Architecture

1. C&DH / Avionics
- JPL Interplanetary CubeSat C&DH Board
- Processing capability for semi-autonomous ops and agile science
- **Leverages: NEA Scout**

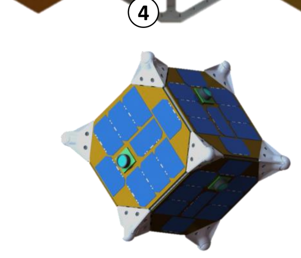
2. Cold Gas Propulsion (Optional)
- For soft landing from ~20m/s deployment
- Alternatively, volume can be used for payload or more batteries
- **Leverages: INSPIRE, MarCO, NEAS**

3. Telecom
- UHF or S band Relay to Mothership
- antennas embedded in frame
- **Leverages: INSPIRE**

4. GNC Sensors/Actuators
- 3 flywheels
- 3+ wide angle cameras
- Sun Sensors + IMU
- Star Tracker
- **Leverages: JPL Visual Odometry frameworks & VSLAM algorithms**



5. Science Instruments
- X-Ray Spectrometer
- Thermocouple
- Microscope
- Cameras + Accelerometers
- **Leverages: APXS (Pathfinder/MER/MSL)**



6. Electrical Power System
- Lithium primary and secondary batteries: >1000 W-h @ 12V
- Optional solar panels
- **Leverages: INSPIRE, MarCO, NEA Scout**

Conclusion

Robotic Exploration of Small Bodies:
- Will be one of NASA's main focuses in years to come
- Requires disruptively new mobility approaches for microgravity environments

Hedgehog Rovers
- New paradigm for in-situ exploration of small bodies
- Technology to obtain new science at an affordable cost
- Controlled mobility demonstrated in simulations and experiments

Ongoing and Future Work:
- Risk-aware motion planning on highly uneven surfaces
- Synergistic localization and navigation strategies with the mothership
- Integration of planning and localization on Hedgehog prototype

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